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# WIND-TUNNEL INVESTIGATION OF AN NACA 65-210 SEMISPAN WING EQUIPPED WITH CIRCULAR PLUG AILERONS AND A FULL-SPAN SLOTTED FLAP

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## SUMMARY

A wind-tunnel investigation was made of the lateral-control characteristics of a thin, low-drag, semispan wing equipped with three configurations of circular plug ailerons and a full-span, 25-percent-chord, slotted flap. The plug ailerons were located at the 68-percent-chord station, spanned 49.2 percent of the semispan wing, and were constructed in five equal spanwise segments. The investigation was performed through a Mach number range from 0.13 to 0.61. The Mach and Reynolds numbers were varied simultaneously during the investigation.

The results of the investigation indicated that a satisfactory plug-aileron configuration (a double-walled circular-plug-aileron configuration) has been developed for use on high-speed unswept-wing airplanes in conjunction with a full-span slotted flap. This plug-aileron configuration produced increases in aileron effectiveness with increase in the Mach and Reynolds numbers, produced a fairly linear variation of rolling moment with aileron projection, and produced appreciably larger rolling moments with the flap deflected than with the flap retracted. In addition, this plug-aileron configuration generally produced favorable yawing moments and also produced hinge moments which were of moderate value, had a stable variation over the projection range, and exhibited either small or inconsistent changes with increases in the Mach and Reynolds numbers.

## INTRODUCTION

As a solution to the high-lift and lateral-control problems presented at take-off and landing by the high-performance airplanes currently in use or in the design stage, the National Advisory Committee for Aeronautics has been investigating the characteristics of spoiler-type lateral-control devices to be used in conjunction with full-span flaps.

The results of several relatively low-speed investigations made on wings having conventional airfoil sections (references 1 to 8) indicated some of the merits of spoiler-type lateral-control devices, such as control at high angles of attack, favorable yawing moments, higher reversal speeds than conventional ailerons because of the lower twisting moments of spoiler-type devices, small stick forces, and the increased effectiveness of spoiler-type controls when full-span flaps are deflected. In addition, these investigations indicated the increased effectiveness obtainable with the plug-type spoiler-slot aileron (known as the "plug aileron") as compared with the effectiveness of the retractable aileron and also indicated the large increase in wing lift obtainable through use of a full-span flap and the generally superior characteristics obtainable with a slotted flap. The results of other investigations performed on unswept wings having high critical speeds (references 9 to 11) showed an increase in aileron effectiveness of the spoiler-type ailerons when the Mach number was increased in the high Reynolds number range as contrasted with a decrease in aileron effectiveness obtained with conventional ailerons as the Mach number increased.

In order to eliminate the unfavorable rolling moments sometimes produced by the downgoing conventional plug aileron and still provide a slot through the wing for up deflections, a new-type plug-aileron arrangement was constructed. The aileron is so designed that down (positive) deflections do not produce any changes in the lower surface of the wing; however, deflecting the aileron up opens a slot and provides a scoop on the lower surface of the wing. The present investigation therefore was performed to ascertain the lateral-control characteristics of a thin, low-drag, semispan wing equipped with a full-span slotted flap and three configurations of the new-type plug aileron. The present investigation, which was performed in the Langley 300 MPH and high-speed 7- by 10-foot tunnels, is an extension of the investigations reported in references 10 and 11 and was performed on the same wing model used in these investigations. Tests of the 0.492-semispan, new-type, plug ailerons - known herein as "circular plug ailerons" to distinguish them from the conventional or regular plug ailerons of references 5, 6, 11, and 12 - were performed through a projection range at several angles of attack with the full-span flap retracted or deflected and at various speeds up to a Mach number of 0.61; lateral-control data obtained in these tests are presented and discussed herein. Wing lift, drag, and pitching-moment data are presented only with the plug aileron and flap in their neutral positions over a speed range up to a Mach number of about 0.835 with the wing at a low angle of attack, since these data had been presented previously through an angle-of-attack range at various speeds with the flap retracted and deflected. (See references 10 and 11.)

## SYMBOLS

The moments on the wing are presented about the wind axes. The X-axis is in the plane of symmetry of the model and is parallel to the tunnel free-stream air flow. The Z-axis is in the plane of symmetry of the model and is perpendicular to the X-axis. The Y-axis is mutually perpendicular to the X-axis and Z-axis. All three axes intersect at the intersection of the chord plane and the 35-percent-chord station at the root of the model.

The symbols used in the presentation of results are as follows:

$C_L$ lift coefficient $\left(\frac{\text{Twice lift of semispan model}}{qS}\right)$

$C_D$ drag coefficient $(D/qS)$

$C_m$ pitching-moment coefficient $\left(\frac{\text{Twice pitching moment of semispan model about Y-axis}}{qS\bar{c}}\right)$

$C_l$ rolling-moment coefficient $(L/qSb)$

$C_n$ yawing-moment coefficient $(N/qSb)$

$C_h$ aileron hinge-moment coefficient $\left(H_a/qM\right.$ where $M$ is area moment of exposed aileron top edge about hinge line$\left.\right)$

$C_{l_p}$ damping-in-roll coefficient $\left(\frac{\partial C_l}{\partial \frac{pb}{2V}}\right)$

$pb/2V$ wing-tip helix angle, radians

$c$ local wing chord

$\bar{c}$ wing mean aerodynamic chord, 2.86 feet $\left(\frac{2}{S}\int_0^{b/2} c^2\, dy\right)$

$b$ twice span of semispan model, 16 feet

$y$ lateral distance from plane of symmetry, feet

$S$ twice area of semispan model, 44.42 square feet

$D$ twice drag of semispan model, pounds

$L$ rolling moment, resulting from aileron projection, about X-axis, foot-pounds

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| $N$ | yawing moment, resulting from aileron projection, about Z-axis, foot-pounds |
| $H_a$ | aileron hinge-moment, positive when hinge moment tends to depress aileron, foot-pounds |
| $q$ | free-stream dynamic pressure, pounds per square foot $\left(\frac{1}{2}\rho V^2\right)$ |
| $V$ | free-stream velocity, feet per second |
| $\rho$ | mass density of air, slugs per cubic foot |
| $\alpha$ | angle of attack with respect to chord plane at root of model, degrees |
| $M$ | Mach number $(V/a)$ |
| $R$ | Reynolds number |
| $a$ | speed of sound, feet per second |

## CORRECTIONS

With the exception of the aileron hinge-moment data, all the data presented are based on the dimensions of the complete wing.

The test data have been corrected for jet-boundary effects according to the methods outlined in reference 13. Compressibility effects on these jet-boundary corrections have been considered in correcting the test data. Blockage corrections were applied to the test data by the methods of reference 14.

## MODEL AND APPARATUS

The right-semispan-wing model was mounted in an inverted position in the Langley high-speed 7- by 10-foot tunnel and in an erect position in the Langley 300 MPH 7- by 10-foot tunnel with its root section adjacent to one of the vertical walls of the tunnel, the vertical wall thereby serving as a reflection plane. (See fig. 1.) The wing was constructed according to the plan-form dimensions shown in figure 2 and had an aspect ratio of 5.76 and a ratio of tip chord to root chord of 0.57. The model was constructed with neither twist nor dihedral and had an NACA 65-210 airfoil section (table I) from root to tip. No transition strips were used on the wing and an attempt was made to keep the model surface smooth during the entire investigation.

The full-span, 0.25c, slotted flap was built to the section dimensions presented in table I and the plan-form dimensions shown in figure 2. The flap deflection (45°) and position with respect to the upper-surface airfoil lip used in the present investigation for the normal flap-deflected position are the same as those employed in the investigations reported in references 10 and 11 and are shown in figure 2.

Each of the circular-plug-aileron configurations tested had a span equal to 49.2 percent of the semispan wing and was fabricated from sheet steel in five equal spanwise segments. Plan-form dimensions of the plug-aileron configurations are shown in figure 2, section dimensions are shown in figure 3, and one of the aileron configurations on the wing model is shown in figure 1. The aileron segments were actuated by $\frac{1}{16}$-inch steel arms which were fastened to each end of each segment and also firmly attached to a steel shaft centered on the aileron hinge axis. This steel shaft extended outside the tunnel wall to a calibrated shaft-rotating mechanism and a calibrated, beam-type, strain-gage setup. By this mechanism, the steel shaft was rotated to produce the various aileron projections employed in the investigation, and the aileron hinge moments were simultaneously obtained.

## TESTS

All tests with the thin-plate circular-plug-aileron configuration (fig. 3(a)) on the semispan-wing model were performed in the Langley high-speed 7- by 10-foot tunnel. All tests with each of the double-walled circular-plug-aileron configurations (figs. 3(b) and (c)) on the semispan-wing model were performed in the Langley 300 MPH 7- by 10-foot tunnel.

With the flap retracted, a speed test was made at a constant wing angle of attack ($\alpha = 0.3°$) through a Mach number range from 0.40 to 0.835 with a corresponding Reynolds number range of approximately $7.5 \times 10^6$ to $12.5 \times 10^6$ based on the mean aerodynamic chord of 2.86 feet.

With the flap retracted or deflected, lateral-control tests were performed with each of the circular plug ailerons at various aileron projections, at several angles of attack, and at Mach numbers from 0.13 to 0.61. Negative projections indicate that the ailerons were extended above the wing upper surface.

The variation of Reynolds number with Mach number for these tests is shown in figure 4. The Mach and Reynolds numbers were varied simultaneously during the investigation.

## DISCUSSION

### Wing Aerodynamic Characteristics

Variation with Mach number of the wing aerodynamic characteristics at a constant angle of attack of 0.3°, with the thin-plate circular plug aileron neutral and the flap retracted, is shown in figure 5. Additional lift, drag, and pitching-moment data were obtained through an angle-of-attack range with each of the double-walled circular-plug-aileron configurations installed on the wing and with the flap retracted and deflected but are not presented herein. These data agree quite well with the data obtained in the pitch tests reported in reference 10 and indicate that installation of any of the circular-plug-aileron configurations on the wing had no material effect in altering the aerodynamic characteristics obtained with the plain wing. Figure 5 shows almost no change in the aerodynamic characteristics for Mach numbers below 0.7; however, above 0.7 somewhat different Mach numbers for lift, drag, and pitching-moment divergence are apparent. Because the choking Mach number of the Langley high-speed 7- by 10-foot tunnel was obtained with the present model at the angle of attack tested near a Mach number of 0.835, the data shown for Mach numbers above approximately 0.80 probably are not reliable.

### Aileron Control Characteristics

Thin-plate circular plug aileron.- Data obtained through the projection range of the thin-plate circular plug aileron are presented in figures 6 to 9 to exhibit the effects of angle of attack and Mach number (also Reynolds number) on the flap-retracted and flap-deflected lateral-control characteristics of the complete wing.

In both the flap-retracted and flap-deflected conditions, the slopes of the curves of rolling-moment coefficient against aileron projection are observed to be generally nonlinear. (See figs. 6 to 9.) In the flap-retracted configuration, an ineffective region for small aileron projections at a low angle of attack is shown and a region of constant or slightly reduced effectiveness (with increase in aileron projection) at large projections and large angles of attack is shown. (See figs. 6 and 7.) The ineffective region observed herein for small aileron projections at a low angle of attack has been observed previously with the basic plug aileron of reference 11 and is believed to result principally from the probably weak "scoop effect" of the particular plug-aileron configuration (because of the square lower edge of the thin-plate circular plug aileron) as will be discussed in a subsequent section of this report - and also from the small differences in pressure existing between the two wing surfaces in the vicinity of the plug slot. At large angles of attack with the flap retracted or with the flap deflected the pressure difference between the two wing surfaces near the plug slot was sufficient to cause the air flow through the plug slot to increase the aileron effectiveness. The region of constant or slightly reduced effectiveness observed at large projections and large angles of attack probably results from the combination of the effects produced by the wing angle of attack (and hence the pressure difference between the two wing surfaces near the plug slot), the position of the lower edge of the plug aileron (which affects the aileron "scoop effect"), and the position of the upper edge of the aileron (which affects any "ram effect" - such as to produce a downward flow through the plug slot).

The aileron effectiveness generally increased with increase in the Mach and Reynolds numbers in both flap conditions. (See figs. 6 and 8.) An exception to this statement is noted in the data shown in figure 6(a), for projections below -5 percent chord, in which a decrease in the effectiveness is observed as the Mach number increased from 0.27 to 0.41. This decrease in effectiveness is similar to the effect observed in the plug-aileron investigation reported in reference 11 and probably results from changes in the wing pressure distribution in the vicinity of the plug slot as the Mach number increased, which effect in turn influenced the flow through the slot and thereby the aileron effectiveness.

Increase of the angle of attack in the flap-retracted condition increased the aileron effectiveness over almost the entire aileron-projection range, particularly for small projections, and tended to linearize the curve of rolling-moment coefficient against aileron projection for projections of less than -3 percent chord. (See figs. 6 and 7.) The aileron effectiveness obtained with flap deflected was considerably larger at all projections than that obtained with flap retracted; the maximum values of $C_l$ obtained with flap deflected were approximately 125 percent larger than the corresponding values obtained with flap retracted. Although no data were obtained above the flap-deflected wing-stall angle, it is believed that the thin-plate circular plug aileron will retain effectiveness in this condition, and the data presented in reference 11 tend to substantiate this belief.

The values of yawing-moment coefficient obtained by projection of the thin-plate circular plug aileron were generally favorable (having the same sign as the values of $C_l$), particularly in the flap-retracted condition, and generally became more positive with increase in aileron projection and less positive with increase in angle of attack. The values of $C_n$ obtained over the projection range generally were less favorable with the flap deflected than with flap retracted. Mach number, as was shown in the investigation reported in reference 11, has only a small effect on the yawing-moment characteristics.

The variation of aileron hinge-moment coefficient with aileron projection was irregular over the projection range. The curves of $C_h$

against aileron projection generally were unstable for small projections, stable for large projections, and became unstable over a greater part of the projection range as $\alpha$ increased. The values of $C_h$ generally were slightly or inconsistently affected by increase in the Mach number, but generally became more negative as the angle of attack increased. (See figs. 6 to 9.) Deflecting the flap resulted in values of hinge-moment coefficient more negative than those obtained with the flaps retracted. Despite the large values shown for the hinge-moment coefficients, which result from the small area upon which the coefficient is based, the actual hinge moments of the plug aileron are very small.

Double-walled circular plug aileron.- The lateral-control characteristics of the double-walled circular plug aileron at various angles of attack and Mach and Reynolds numbers are presented in figures 10 and 11 for the flap-retracted condition and in figures 12 and 13 for the flap-deflected condition. It will be noted that the Mach number range covered in tests of this configuration was quite small and in the range of Mach number where compressibility effects are usually small; therefore, any aerodynamic effects occurring as a result of changing the Mach and Reynolds numbers (simultaneously) are probably mostly Reynolds number effects. In the ensuing discussion, Mach and Reynolds number changes are not discussed where the aerodynamic effects produced by such changes are negligible.

The variation of rolling-moment coefficient with aileron projection is observed to be fairly linear over most of the aileron-projection range for the flap-retracted condition but generally slightly nonlinear for the flap-deflected condition. Increases in the Mach and Reynolds numbers generally resulted in increases in the aileron effectiveness for either flap condition. (See figs. 10 and 12.) It is anticipated that the aileron effectiveness of the double-walled circular plug aileron would exhibit additional increases (similar to those exhibited by the plug ailerons of reference 11 and the thin-plate circular plug ailerons of the present investigation) when the Mach and Reynolds numbers are increased beyond the range of the present investigation and up to the critical Mach number.

Increase in the wing angle of attack resulted in an increase in the aileron effectiveness over most of the aileron-projection range in the flap-retracted condition and generally resulted in a decrease in the aileron effectiveness over the aileron-projection range in the flap-deflected condition. The aileron effectiveness obtained with flap deflected was considerably larger at all projections than that obtained with flap retracted; the maximum values of $C_l$ obtained with flap deflected were about 85 percent larger than the maximum values of $C_l$ obtained with flap retracted. The data of figure 12(d) (which were obtained above the flap-deflected wing stall angle) also indicate that the double-walled circular plug aileron was quite effective and produced large rolling moments above the flap-deflected stall angle. It will be noted that small favorable rolling moments were produced by positive aileron projections for both flap conditions. Although the upper edge of the aileron is below the upper-surface wing contour for positive aileron projections and the lower edge of the aileron extends no further below the lower-surface wing contour than it does when neutral, the favorable rolling moments are thought to result from the more complete plug-slot seal produced by positive aileron projections.

The values of yawing-moment coefficient produced by projection of the double-walled circular plug aileron were generally favorable and became more favorable with increase in aileron projection with the flap retracted but were generally favorable only for large aileron projections with the flap deflected. The values of $C_n$ generally were more favorable with the flap retracted than with the flap deflected and became less favorable with increase in the wing angle of attack in either flap condition. (See figs. 10 to 13.)

The variation of hinge-moment coefficient with aileron projection was only slightly irregular and was generally stable in the negative projection range in both flap conditions and became less stable over most of the projection range as the wing angle of attack increased. Deflection of the flap resulted in a larger variation of $C_h$ over the projection range and in values of $C_h$ more negative than those obtained with the flap retracted.

Modified double-walled circular plug aileron.- The characteristics of the double-walled circular plug aileron modified by removing the 0.015c top plate and replacing it with one as wide as the aileron forward wall (3/32 inch) are shown in figures 14 to 17. As was discussed in the preceding section for the unmodified double-walled circular plug aileron, the Mach number range covered in tests of this modified aileron was quite small and in the range of Mach number where compressibility effects are usually small. In the ensuing discussion, Mach and Reynolds number changes are not discussed when the aerodynamic effects produced by such changes are negligible; when these aerodynamic effects are significant, they probably result mostly from changes in Reynolds number.

The aileron-effectiveness characteristics of this modified plug aileron were generally quite similar to the characteristics of the unmodified plug aileron discussed in the preceding section. The values of $C_l$ obtained with the modified aileron were fairly linear over most of the aileron projection range in both flap conditions and increased with increase in the Mach and Reynolds numbers. In addition, when the wing angle of attack was increased, the values of $C_l$ generally increased in the flap-retracted condition and decreased in the flap-deflected condition. The data of figures 14 to 17 also indicate that the aileron effectiveness with flap deflected was appreciably larger than that obtained with flap retracted (approximately 85 percent larger for maximum values of $C_l$) and that the modified aileron was quite effective up to and above the angle of wing stall. (Compare the values of $C_L$ and $\alpha$ with corresponding values from reference 10.)

The yawing-moment characteristics of the modified plug aileron were generally similar to those of the unmodified aileron; the same effects and trends of the $C_n$ curves with changes in angle of attack and flap deflection discussed in the preceding section for the unmodified aileron generally were obtained with the modified plug aileron.

The variation of hinge-moment coefficient with projection of the modified plug aileron was markedly nonlinear, and generally became less stable (or more unstable) over a greater part of the negative projection range as the wing angle of attack increased. In addition, the values of $C_h$ generally became more negative as the wing angle of attack increased, and more negative values of $C_h$ were generally obtained with the flap deflected than with the flap retracted. (See figs. 14 to 17.) The aforementioned effects on $C_h$, when compared with the $C_h$ data of the unmodified double-walled circular plug aileron, are generally the effects expected to result from removing the aileron top plate and have been found in previous investigations. (See references 5 and 11.)

## Comparison of Lateral-Control Characteristics of the Three Configurations of Circular Plug Aileron

For purposes of direct comparison, some of the lateral-control data previously presented for the thin-plate, double-walled, and modified double-walled circular plug ailerons have been replotted for similar test conditions in the same figure and are shown in figures 18 and 19. A more complete comparison of these data can be made with figures 6 to 17.

For each of the three circular-plug-aileron configurations investigated, increases in the aileron effectiveness with increase in Mach and Reynolds numbers were generally obtained in both the flap-retracted and flap-deflected conditions. In the flap-retracted condition, the aileron effectiveness of each of the circular plug ailerons increased when the angle of attack increased; the thin-plate circular plug aileron exhibited the largest effects on $C_l$ produced by changes in $\alpha$. In the flap-deflected condition, increases in $\alpha$ had an inconsistent effect on the aileron effectiveness of the thin-plate plug aileron but generally tended to decrease the aileron effectiveness of each of the double-walled plug ailerons. Deflecting the flap had more effect in increasing the values of $C_l$ for the thin-plate plug aileron than for either of the double-walled plug ailerons.

The thin-plate plug aileron generally produced larger values of $C_l$ over the projection range in both flap conditions than did either of the double-walled plug ailerons, except possibly at low values of $\alpha$ with the flap retracted. As may be seen from the data in figures 6 to 19, each of the double-walled circular plug ailerons produced a more linear variation of $C_l$ over the projection range than did the thin-plate circular plug aileron, and the double-walled plug ailerons did not exhibit the ineffective region exhibited by the thin-plate plug aileron for small projections at a low angle of attack with the flap retracted. The greater linearity exhibited by the rolling-moment curves of the double-walled circular plug aileron over the projection range is thought to result from a dual effect produced by the basic physical differences between the double-walled and thin-plate plug-aileron configurations. At small aileron projections and low angles of attack the beveled lower edge of the double-walled plug aileron produces a greater "scoop effect" and hence a greater aileron effectiveness than the thin-plate plug aileron. At all aileron projections and large angles of attack, the upper edge of the double-walled plug aileron permits the air flowing up through the plug slot to exit behind the aileron, whereas the air would exit ahead of the upper edge of the thin-plate plug aileron; thus, the combination "ram effect" at the upper edge and the "scoop effect" at the lower edge of the thin-plate plug aileron probably offset each other in some manner to produce the region of constant or reduced aileron effectiveness observed in figure 18(b) and in figures 6 and 7.

Computations to determine the helix angle $pb/2V$ generated by the wing tip in a roll were made by utilizing the relationship $\frac{pb}{2V} = \frac{C_l}{C_{l_p}}$, where $C_{l_p}$ is the damping-in-roll coefficient, and indicated the large rolling effectiveness of the circular plug ailerons investigated, particularly in the flap-deflected condition. These computations showed that a value of $C_l$ of 0.036, which was usually exceeded at large aileron projections with the flap retracted and easily exceeded with the flap deflected, corresponded to a value of $pb/2V$ of 0.09, based on a value of $C_{l_p}$ (obtained from reference 15) of 0.40.

The yawing-moment characteristics of the three circular plug ailerons investigated were generally similar and exhibited the same trends with change in the Mach and Reynolds numbers, angle of attack, and flap deflection.

The data for the unmodified double-walled circular plug aileron exhibited the most stable variation of $C_h$ and the smallest variation of $C_h$ over the aileron-projection range of the three circular plug ailerons investigated. Because the area moments of the top edge of the thin-plate and the modified double-walled plug ailerons were almost similar, these ailerons exhibited generally similar variations and values of $C_h$ over the projection range. For each of the circular plug ailerons, the curves of $C_h$ against aileron projection generally became less stable and the values of $C_h$ generally became more negative as $\alpha$ increased. In general, the values of $C_h$ for each of the circular plug ailerons were only slightly affected by changes in the Mach and Reynolds numbers, and more negative values of $C_h$ were generally produced by each of the circular plug ailerons with the flap deflected than with the flap retracted.

It is well to note that the hinge moments of the double-walled circular plug aileron are of fairly moderate value, whereas the hinge moments produced by the thin-plate and modified double-walled circular plug ailerons are extremely small. These hinge moments may be masked in an airplane installation by a booster system, a mechanical device providing "stick feel," or by a "feeler aileron" (reference 16). For example, the hinge moments produced on the model investigated herein at a dynamic pressure of 200 pounds per square foot (approx. 300 mph) and at a value of $C_h$ of 1.0 were approximately 1.2, 5.4, and 1.1 foot-pounds for the thin-plate, the double-walled, and the modified double-walled circular plug ailerons, respectively.

## Comparison of Lateral-Control Characteristics of the Circular Plug Ailerons, a Conventional Plug Aileron, and a Retractable Aileron

Comparisons were made of the lateral-control characteristics of the circular plug ailerons of the present investigation with the corresponding characteristics of the conventional plug and retractable ailerons reported in reference 11. Several of these comparisons are shown in figures 18 and 19.

Larger values of rolling-moment coefficient generally were obtained over the projection range in both flap conditions with each of the circular plug ailerons than with either the conventional plug or retractable ailerons. One notable exception to this statement is observed for the flap-retracted condition at a low angle of attack where the thin-plate circular plug aileron is seen to be less effective, for small projections, than either of the other spoiler-type devices. (See fig. 18(a).) The ineffective region at low projections and low angles of attack exhibited by the thin-plate circular plug aileron is quite similar to the results obtained on the conventional plug without the top plate (reference 11); and, as previously indicated, modifying this circular plug aileron by beveling the lower edge of the aileron and installing a double plug wall and a top plate, thereby producing the double-walled circular plug aileron, alleviated this condition appreciably. The two double-walled circular plug ailerons thereby produced more linearity in the variation of $C_l$ with aileron projection than either of the other ailerons. The circular plug ailerons also exhibited larger increases in aileron effectiveness than either of the other ailerons when the angle of attack was increased in the flap-retracted condition. In addition, the circular plug ailerons showed the same trends of $C_l$ with flap deflection and with increase in the Mach and Reynolds numbers as the conventional plug and retractable ailerons.

The values of $C_n$ obtained with each of the circular plug ailerons generally were slightly more positive (more favorable) in all configurations than those obtained with either the conventional plug or retractable ailerons. (See figs. 18 and 19.) The trends of $C_n$ with angle of attack, flap deflection, and Mach and Reynolds numbers were the same for the ailerons of the subject investigation as for the ailerons of the investigation reported in reference 11.

The thin-plate and modified double-walled circular plug ailerons displayed a larger variation of $C_h$ over the projection range in the flap-retracted condition than either the conventional plug or retractable ailerons considered in the comparison, whereas the variation of $C_h$ with projection for the unmodified double-walled circular plug aileron was almost similar to that of the conventional plug and retractable ailerons. Generally, a less stable variation of $C_h$ over a larger part of the projection range was displayed by the thin-plate and modified double-walled circular-plug-aileron data, and a more stable variation of $C_h$ over the projection range was displayed by the data for the unmodified double-walled circular plug aileron than by the data for the conventional plug and retractable ailerons. The hinge-moment-coefficient curves of the circular plug ailerons showed slightly larger effects produced by changes in the angle of attack and flap deflection and about the same effects produced by changes in the Mach and Reynolds numbers as the $C_h$ curves of the conventional plug and retractable ailerons.

It would therefore appear that the main advantages to be gained by using any of the subject plug ailerons instead of the conventional plug aileron are to eliminate the adverse rolling moments produced by the downgoing conventional plug and to provide larger rolling moments for a given plug-aileron projection.

### Comparison of Lateral-Control Characteristics of the Circular Plug Ailerons with Those of a Sealed Plain Aileron

The variation of helix angle $pb/2V$ and aileron hinge moment with deflection (or projection) of the double-walled circular plug aileron and a 0.20c, $0.38 \frac{b}{2}$, sealed plain aileron investigated on the same wing (reference 10) are compared for several representative conditions in the flap-retracted condition in figure 20. As was discussed in a preceding section, the helix angle was computed from the relationship $\frac{pb}{2V} = \frac{C_l}{C_{l_p}}$ and the value of $C_{l_p}$ employed was 0.40.

The comparison shown in figure 20 illustrates the effectiveness of both types of lateral-control devices and, in particular, the degree of linearity of the plug-aileron effectiveness over the deflection (or projection) range, especially near zero deflection. Further comparisons of the circular-plug-aileron data with the plain-aileron data of reference 10 illustrate the increase in aileron effectiveness with increase in the angle of attack and Mach and Reynolds numbers obtained with the circular plug ailerons contrasted with opposite effects obtained with the sealed plain aileron. Also, the plug ailerons produced extremely large values of rolling moment in the flap-deflected condition and were quite effective above the flap-deflected stall angle; whereas the plain-aileron effectiveness probably would not be increased by deflecting the flap and probably would be inadequate above the wing stall. It should also be noted that plug ailerons permit use of full-span flaps - with an accompanying increase in airplane performance - whereas plain ailerons restrict the flap span.

A comparison of the yawing-moment data obtained with the present plug ailerons and the plain aileron of reference 10 shows the generally favorable yawing characteristics - such as to increase aileron effectiveness - of the plug ailerons contrasted with the unfavorable yawing characteristics of the plain aileron.

The hinge moments of the double-walled circular plug aileron (as well as those of the other circular plug ailerons) are extremely small compared with the hinge moments of the plain aileron (fig. 20) and indicate a marked degree of linearity over the deflection range. The hinge moments presented in figure 20 were computed for the ailerons on the present wing; therefore, if these controls were applied to a specific airplane, the hinge moments would be magnified by the cube of the ratio of airplane wing span to model wing span. Because the hinge moments of the plug ailerons investigated were relatively unaffected by increase in Mach number and these ailerons produced small hinge moments that could be altered (references 5, 6, and 11) or masked, large control deflections, hence control, would be available at all speeds. Conversely, the plain ailerons of reference 10 exhibited adverse affects of Mach number on the hinge moments, and the large hinge moments obtained at high speeds probably would limit the aileron deflection and the lateral control of the airplane.

## CONCLUSIONS

A wind-tunnel investigation was made of the lateral-control characteristics of a thin, low-drag, semispan wing equipped with three configurations of circular plug ailerons and a full-span, 25-percent-chord, slotted flap. The plug ailerons were located at the 68-percent-chord station, spanned 49.2 percent of the semispan wing, and were constructed in five equal spanwise segments. The investigation was performed through a Mach number range from 0.13 to 0.61. The Mach and Reynolds numbers were varied simultaneously during the investigation. The results of the investigation led to the following conclusions:

1. For each of the three circular-plug-aileron configurations investigated, increases in the aileron effectiveness with increase in Mach and Reynolds numbers were generally obtained in both the flap-retracted and flap-deflected conditions. In the flap-retracted condition, the aileron effectiveness of each of the circular plug ailerons increased when the angle of attack was increased; the thin-plate circular plug aileron exhibited the largest increases in aileron effectiveness with increase in angle of attack. In the flap-deflected condition, increase in angle of attack had an inconsistent effect on the rolling moments produced by the thin-plate circular plug aileron but generally tended to decrease the aileron effectiveness of each of the double-walled circular plug ailerons investigated. Appreciably larger values of rolling-moment coefficient were produced by each of the circular plug ailerons with the full-span flap deflected than were produced with the flap retracted, and the ailerons produced large rolling moments up to and above the flap-deflected stall angle. The thin-plate circular plug aileron generally produced larger values of rolling-moment coefficient in both flap conditions than did either of the double-walled circular plug ailerons, but the double-walled circular plug ailerons produced a more linear variation of rolling moment over the aileron-projection range.

2. Each of the circular plug ailerons produced yawing moments that were generally favorable, became more favorable with aileron projection, less favorable with increase in angle of attack and flap deflection, and were only slightly affected by increases in the Mach and Reynolds numbers.

3. The variation of hinge-moment coefficient with aileron projection for each of the circular plug ailerons was nonlinear and exhibited either small or inconsistent changes with increase in Mach and Reynolds numbers. The double-walled circular plug aileron equipped with a top plate exhibited the most linear variation of hinge-moment coefficient with aileron projection and also had a fairly stable variation of hinge moment with projection. For each of the ailerons, the variation of hinge-moment coefficient with projection became less stable over a greater part of the projection range

and the values of hinge-moment coefficient became more negative as the angle of attack increased. In addition, more negative values of hinge-moment coefficient were generally produced by each of the ailerons with flap deflected than with the flap retracted.

Langley Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Air Force Base, Va., December 1, 1948

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TABLE I.- ORDINATES FOR AIRFOIL AND FLAP

[All dimensions given in percent of wing chord]

NACA 65-210 airfoil

| Upper surface | | Lower surface | |
|---|---|---|---|
| Station | Ordinate | Station | Ordinate |
| 0 | 0 | 0 | 0 |
| .435 | .819 | .565 | -.719 |
| .678 | .999 | .822 | -.859 |
| 1.169 | 1.273 | 1.331 | -1.059 |
| 2.408 | 1.757 | 2.592 | -1.385 |
| 4.898 | 2.491 | 5.102 | -1.859 |
| 7.394 | 3.069 | 7.606 | -2.221 |
| 9.894 | 3.555 | 10.106 | -2.521 |
| 14.899 | 4.338 | 15.101 | -2.992 |
| 19.909 | 4.938 | 20.091 | -3.346 |
| 24.921 | 5.397 | 25.079 | -3.607 |
| 29.936 | 5.732 | 30.064 | -3.788 |
| 34.951 | 5.954 | 35.049 | -3.894 |
| 39.968 | 6.067 | 40.032 | -3.925 |
| 44.984 | 6.058 | 45.016 | -3.868 |
| 50.000 | 5.918 | 50.000 | -3.709 |
| 55.014 | 5.625 | 54.986 | -3.435 |
| 60.027 | 5.217 | 59.973 | -3.075 |
| 65.036 | 4.712 | 64.964 | -2.652 |
| 70.043 | 4.128 | 69.957 | -2.184 |
| 75.045 | 3.479 | 74.955 | -1.689 |
| 80.044 | 2.783 | 79.956 | -1.191 |
| 85.038 | 2.057 | 84.962 | -.711 |
| 90.028 | 1.327 | 89.972 | -.293 |
| 95.014 | .622 | 94.986 | .010 |
| 100.000 | 0 | 100.000 | 0 |

L.E. radius: 0.687
Slope of radius through L.E.: 0.084

Slotted flap

| Upper surface | | Lower surface | |
|---|---|---|---|
| Station | Ordinate | Station | Ordinate |
| 0 | 0 | 0 | 0 |
| .28 | .92 | .28 | -.41 |
| .56 | 1.19 | .56 | -.62 |
| 1.12 | 1.56 | 1.12 | -.88 |
| 1.69 | 1.80 | 1.69 | -1.00 |
| 2.25 | 1.99 | 2.48 | -1.03 |
| 3.38 | 2.22 | 4.98 | -.83 |
| 4.50 | 2.33 | 7.48 | -.63 |
| 5.61 | 2.38 | 9.98 | -.44 |
| 7.00 | 2.40 | 12.48 | -.27 |
| 9.00 | 2.35 | 14.98 | -.12 |
| 11.00 | 2.16 | 17.48 | .01 |
| 12.51 | 1.91 | 19.99 | .10 |
| 15.01 | 1.50 | 22.49 | .12 |
| 17.51 | 1.10 | 25.00 | 0 |
| 20.00 | .71 | | |
| 22.50 | .34 | | |
| 25.00 | 0 | | |

L.E. radius: 0.80
Slope of radius through L.E.: 0.35

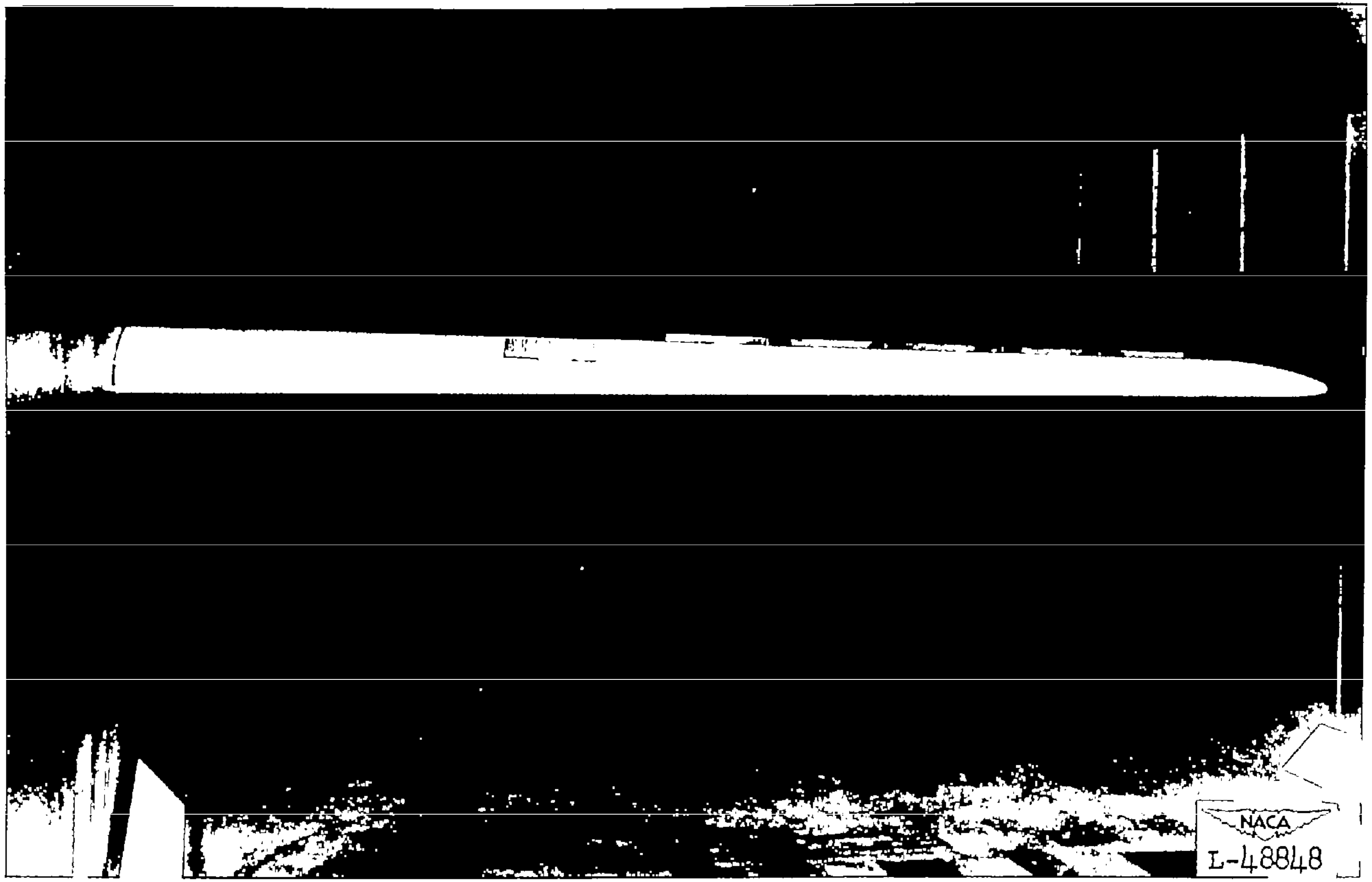



Figure 1.— Front view of the reflection—plane model in inverted position in the Langley high—speed 7— by 10—foot tunnel. Full—span slotted flap retracted.

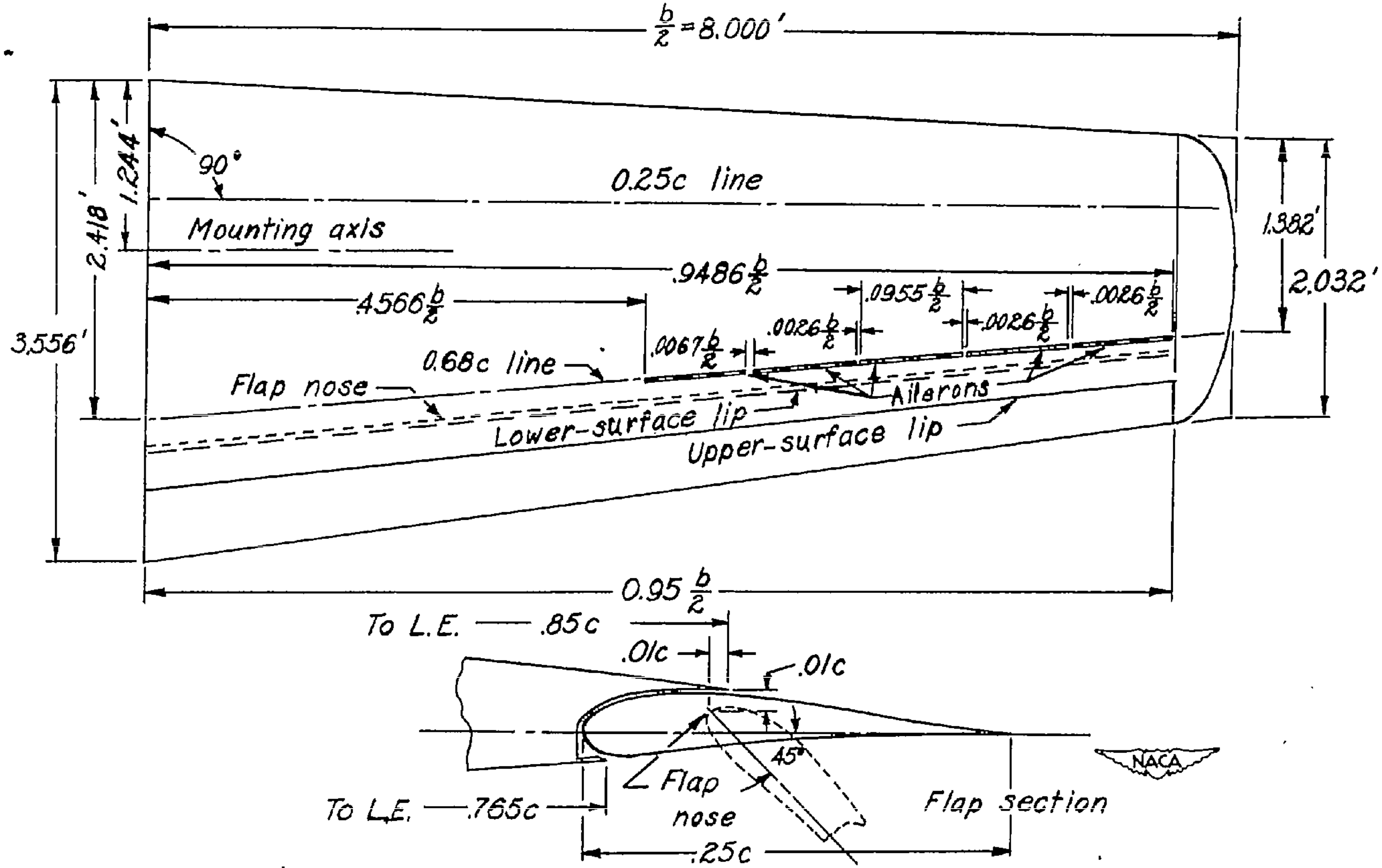
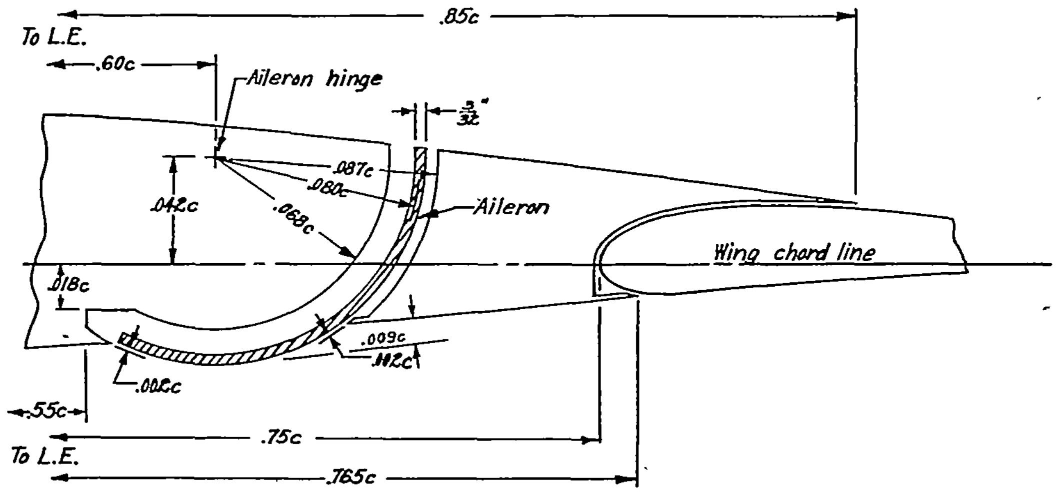
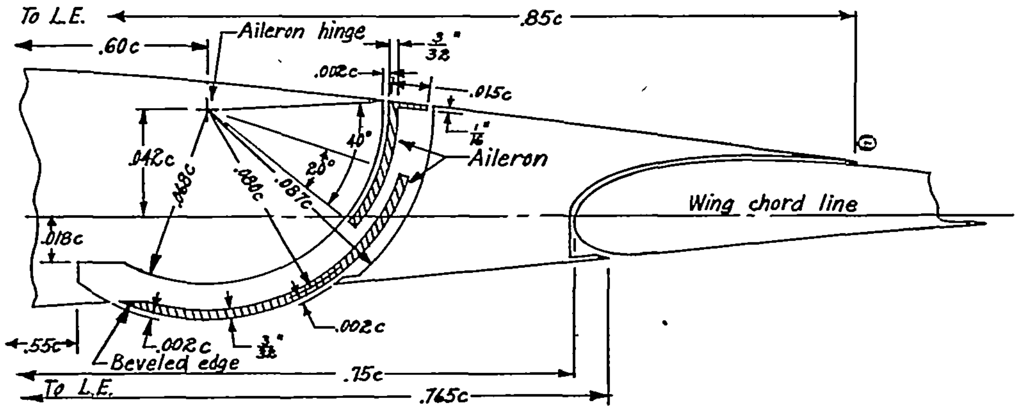


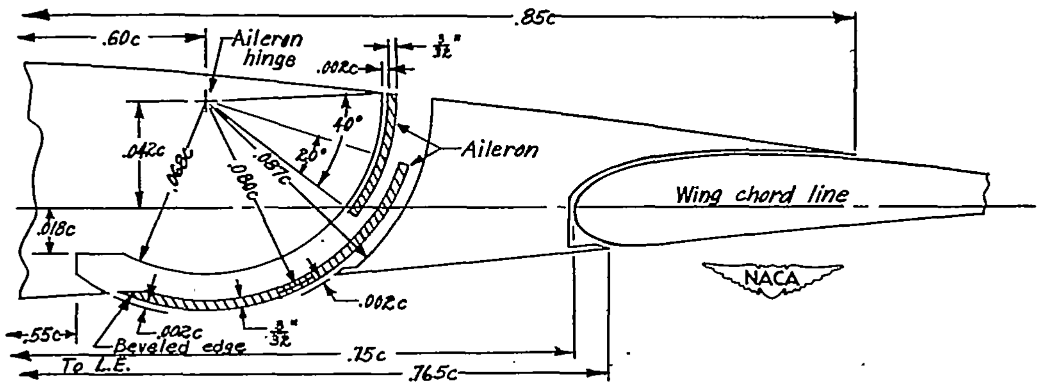

Figure 2.– Schematic drawing of right-semispan-wing model equipped with circular plug ailerons and a full-span slotted flap.




(a) Thin-plate circular-plug-aileron configuration.




(b) Double-walled circular-plug-aileron configuration.




(c) Double-walled circular-plug-aileron configuration with 0.015c top plate removed from aileron.

Figure 3.– Schematic drawing of circular-plug-aileron configurations tested on semispan wing.

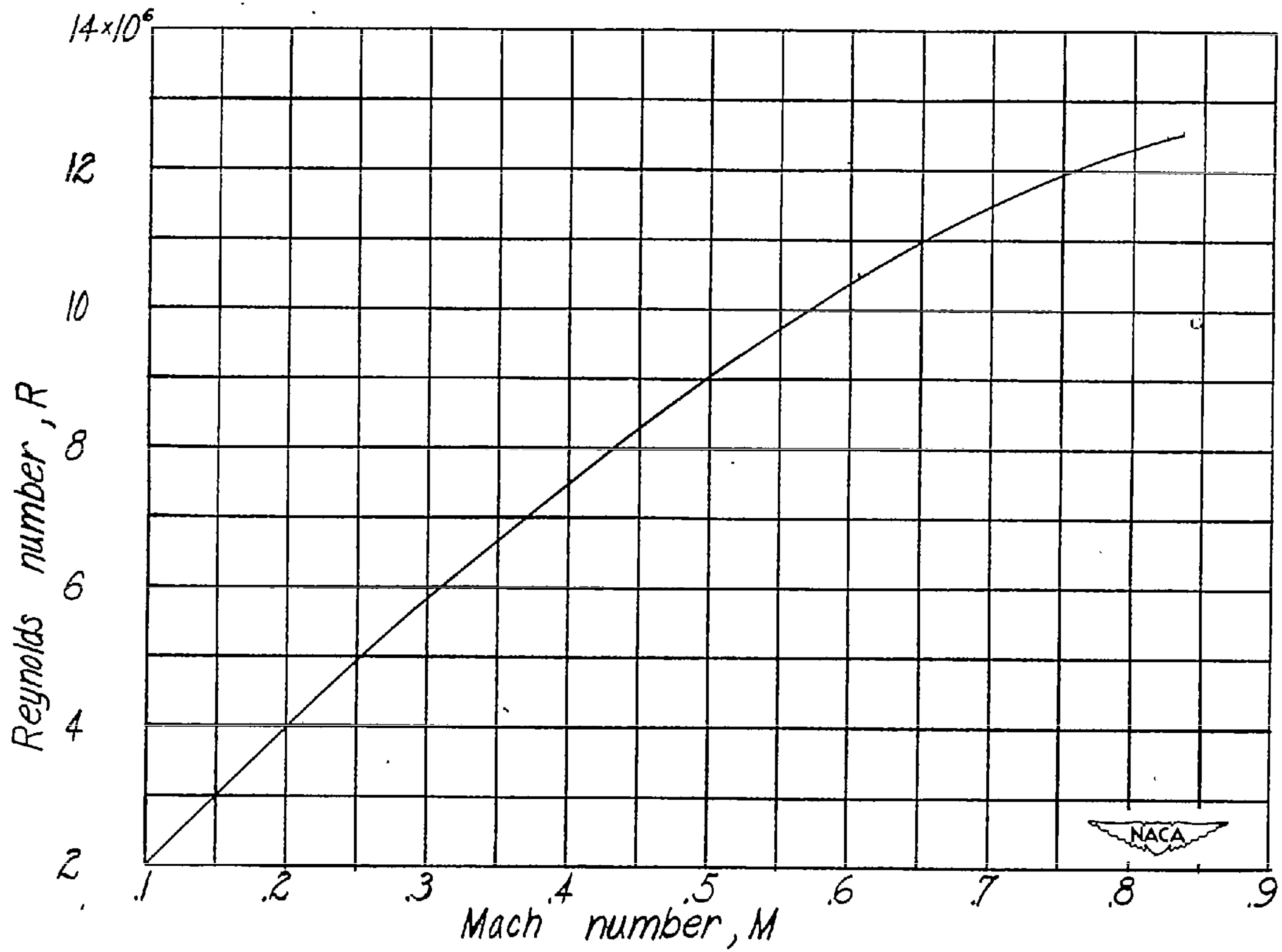



Figure 4.– Variation of Reynolds number with Mach number. Reynolds number is based on wing mean aerodynamic chord of 2.86 feet.

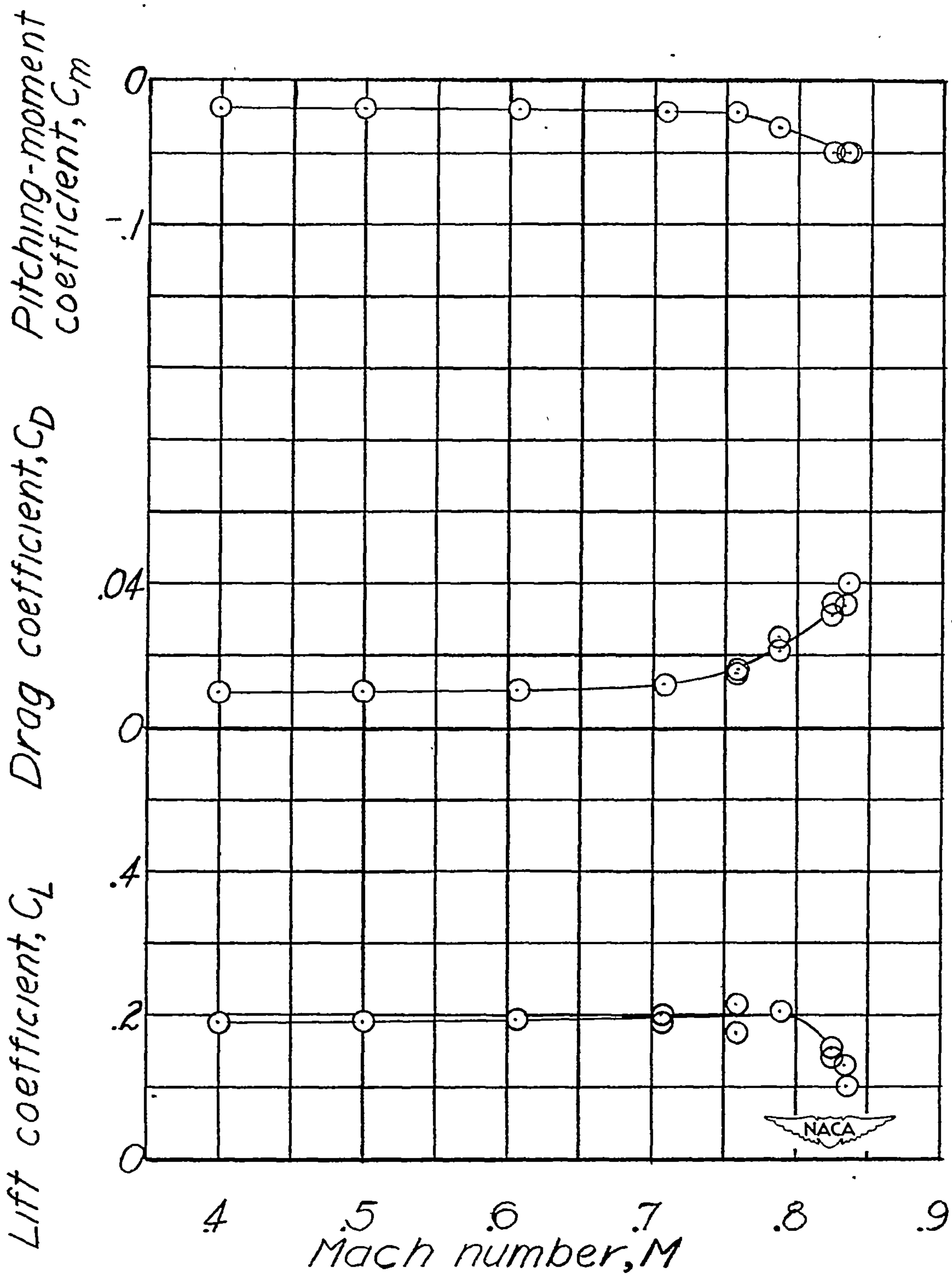
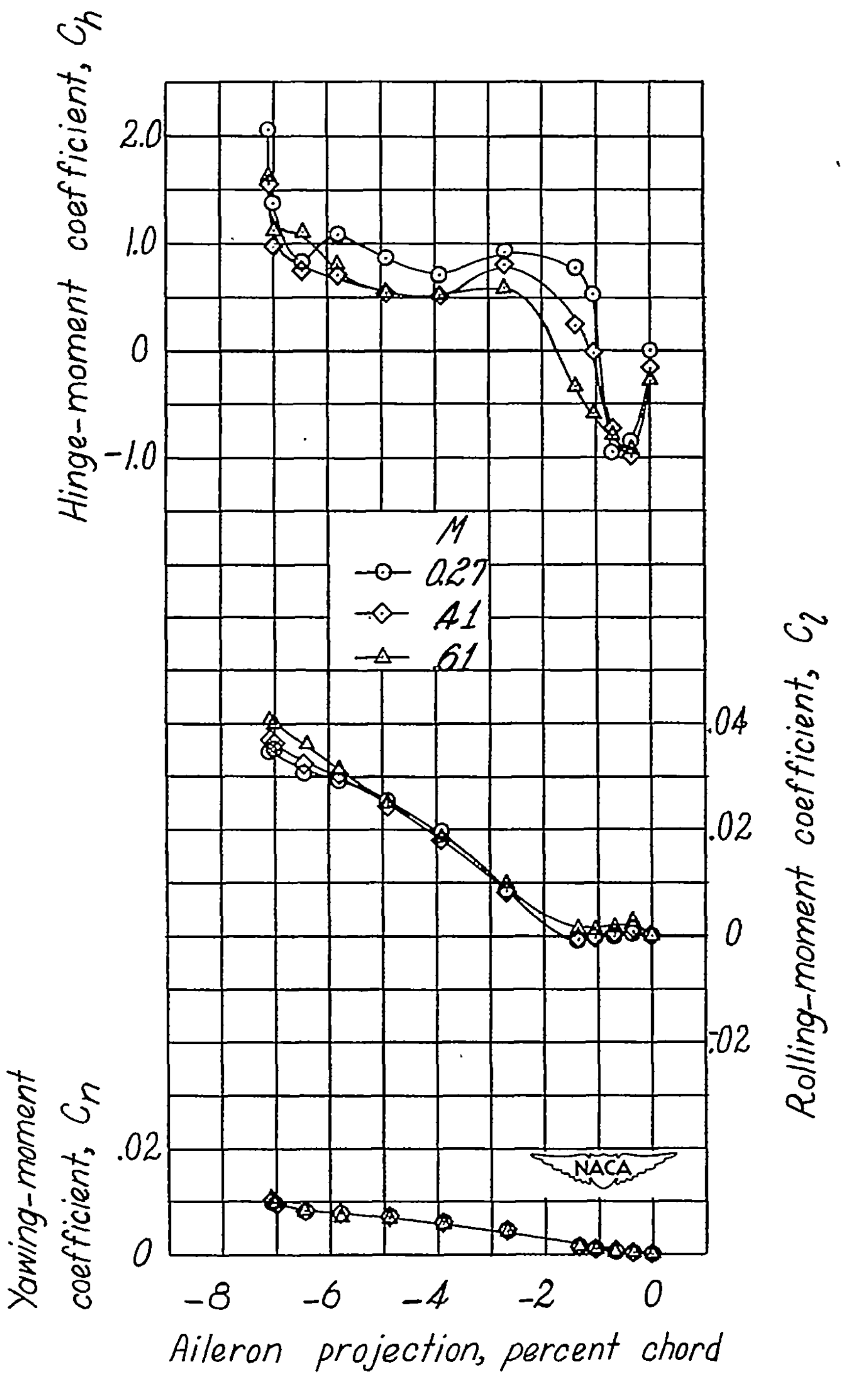
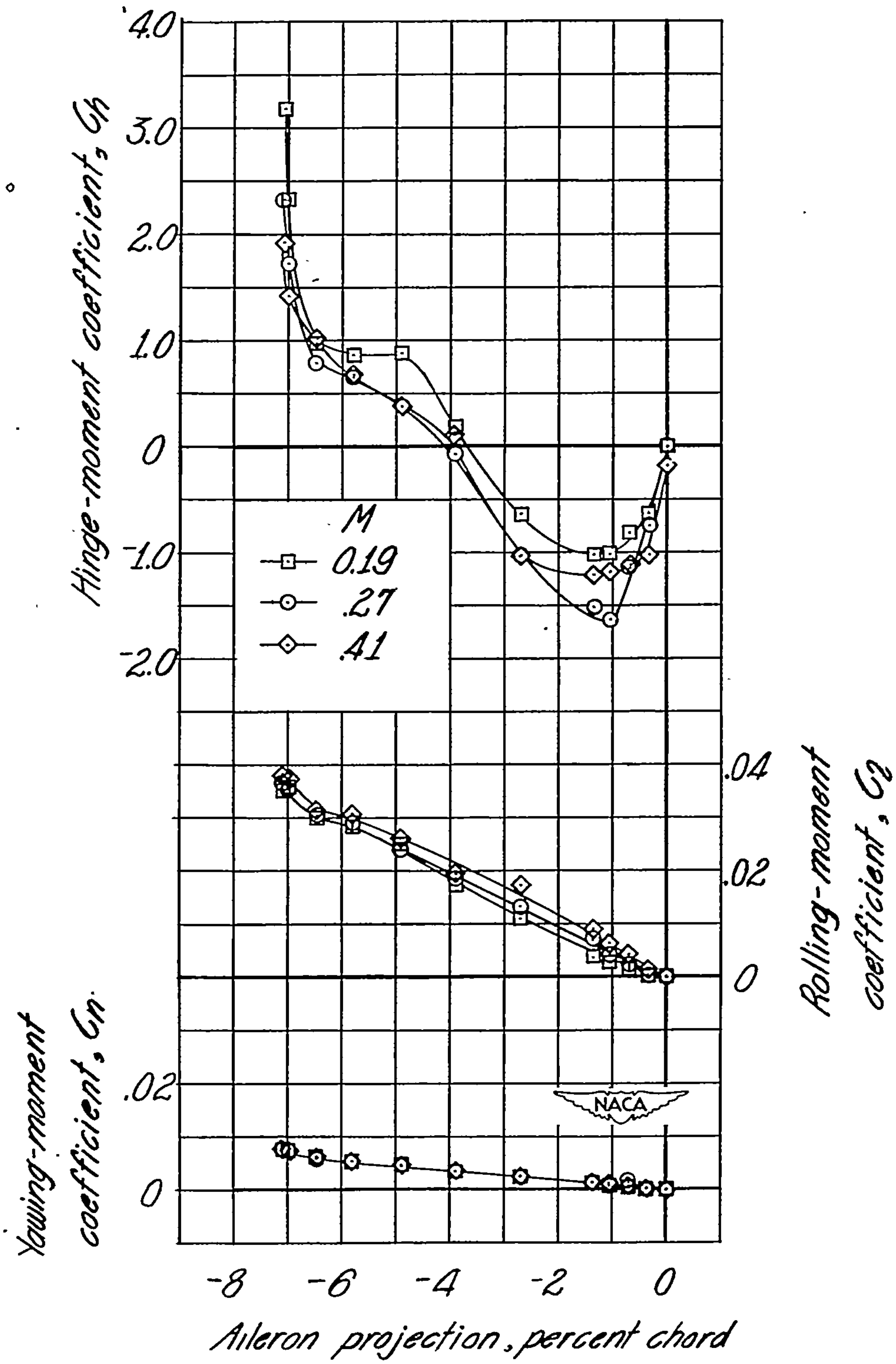



Figure 5.– Variation with Mach number of aerodynamic characteristics of semispan-wing model with flap retracted. Thin-plate circular plug aileron neutral. $\alpha = 0.3^{\circ}$.



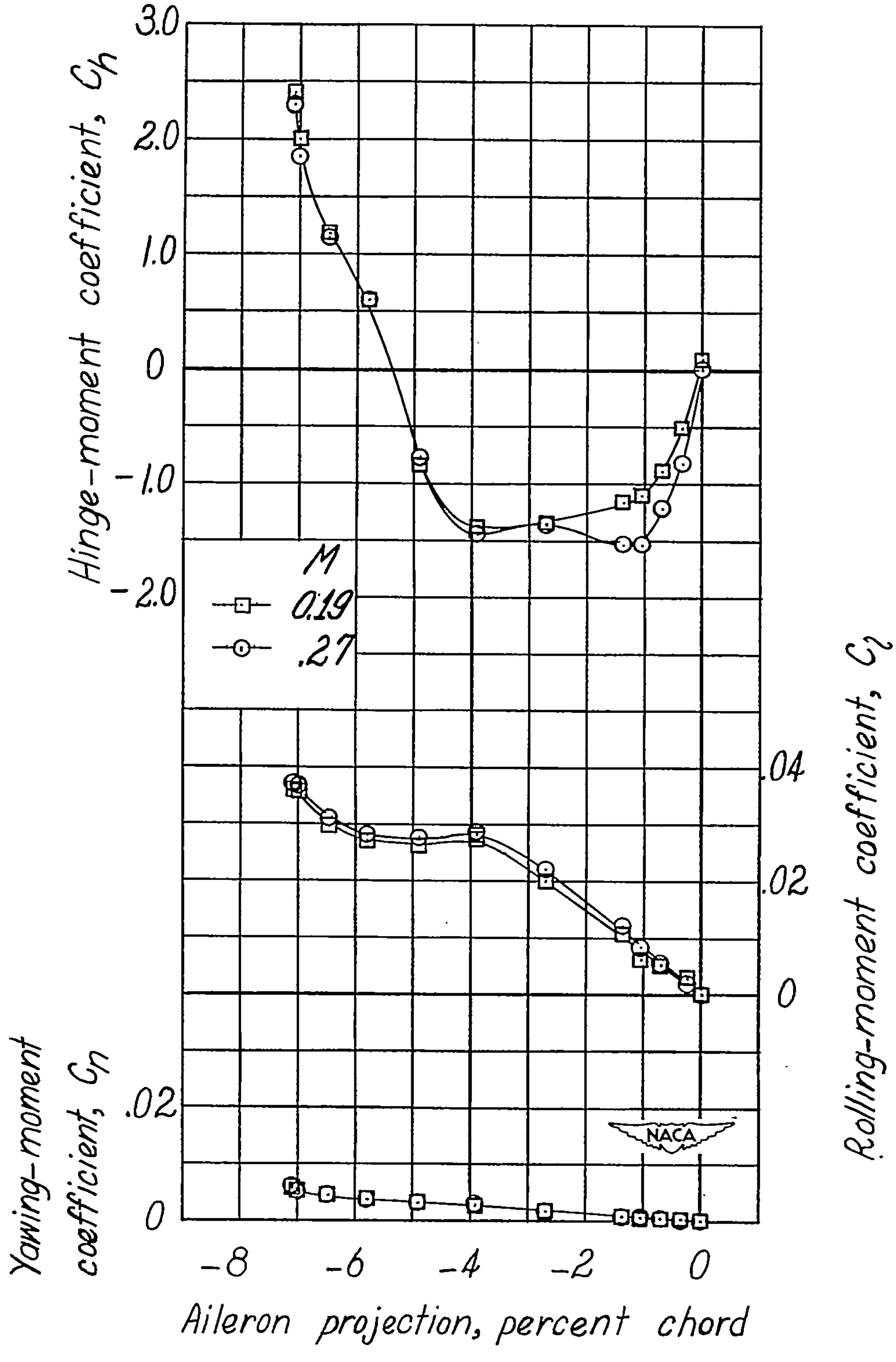

(a) $\alpha \approx 0.2^{\circ}$; $C_L \approx 0.14$.

Figure 6.– Variation of lateral-control characteristics of complete wing with projection of thin-plate circular plug aileron at various Mach numbers. Flap retracted.



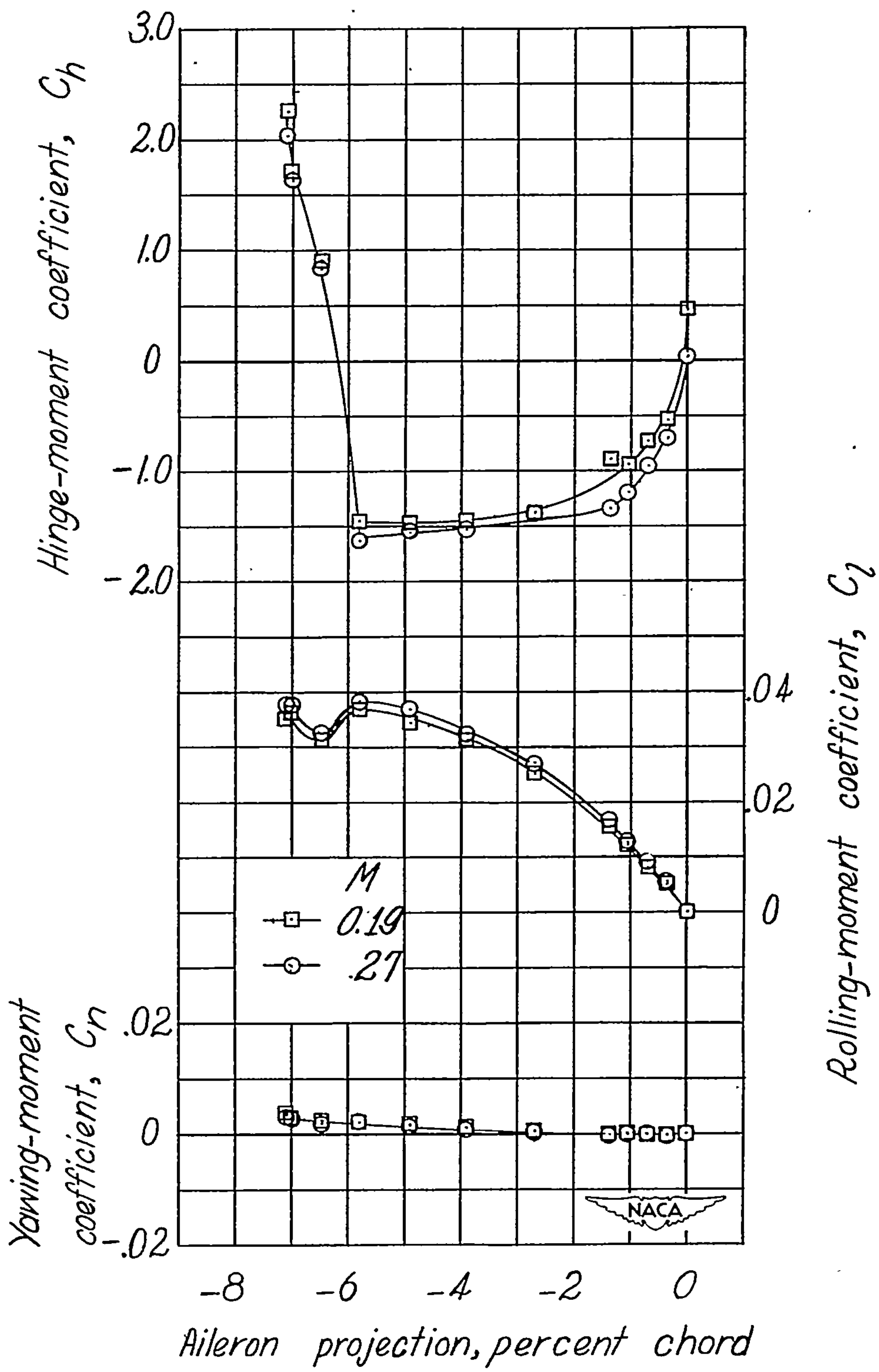

(b) $\alpha \approx 4.8^{\circ}$; $C_L \approx 0.47$.

Figure 6.– Continued.




(c) $\alpha \approx 8.2^{\circ}$; $C_L \approx 0.72$.

Figure 6.– Continued.




(d) $\alpha \approx 11.7^{\circ}$; $C_L \approx 1.01$.

Figure 6.– Concluded.

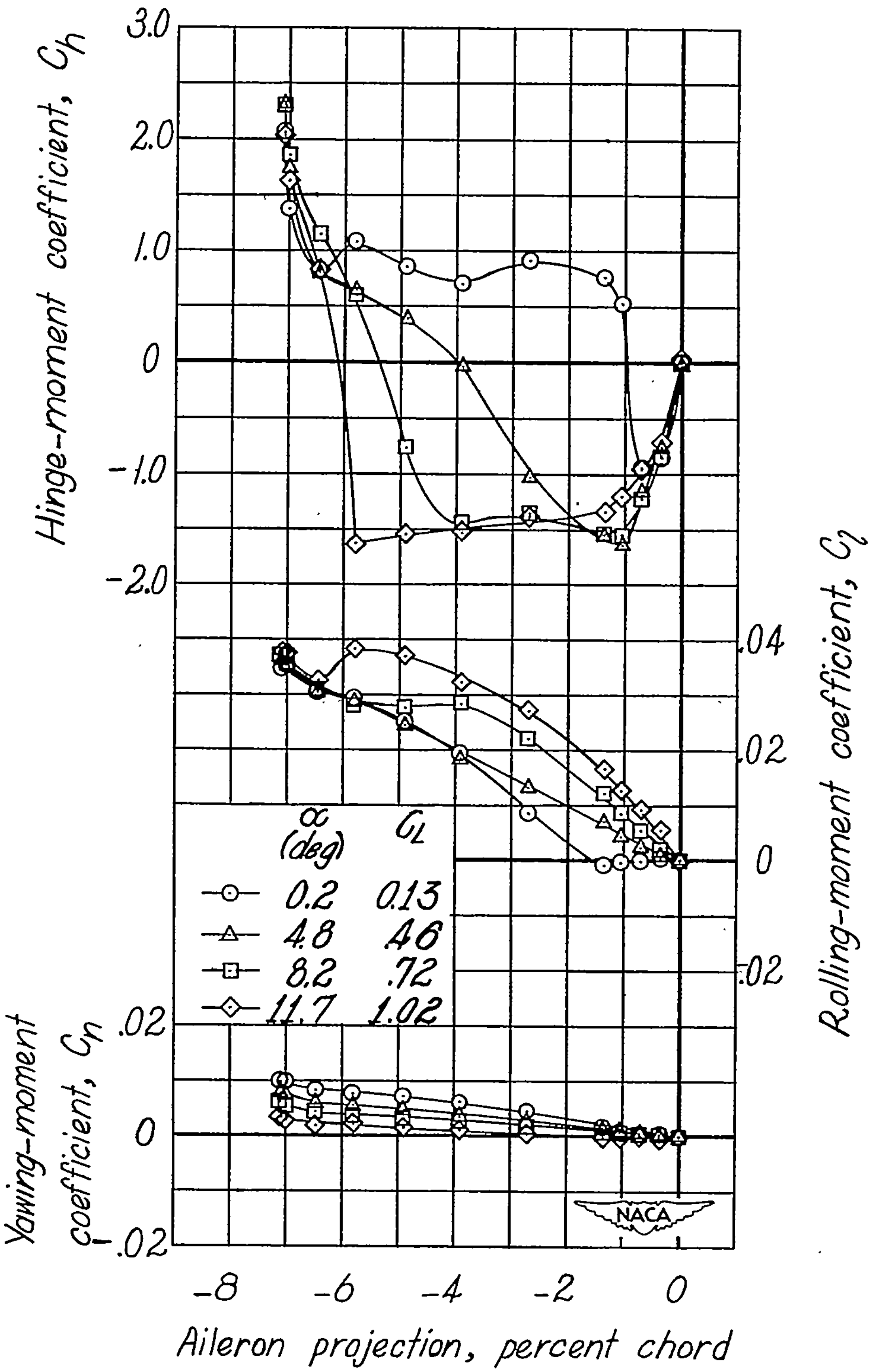
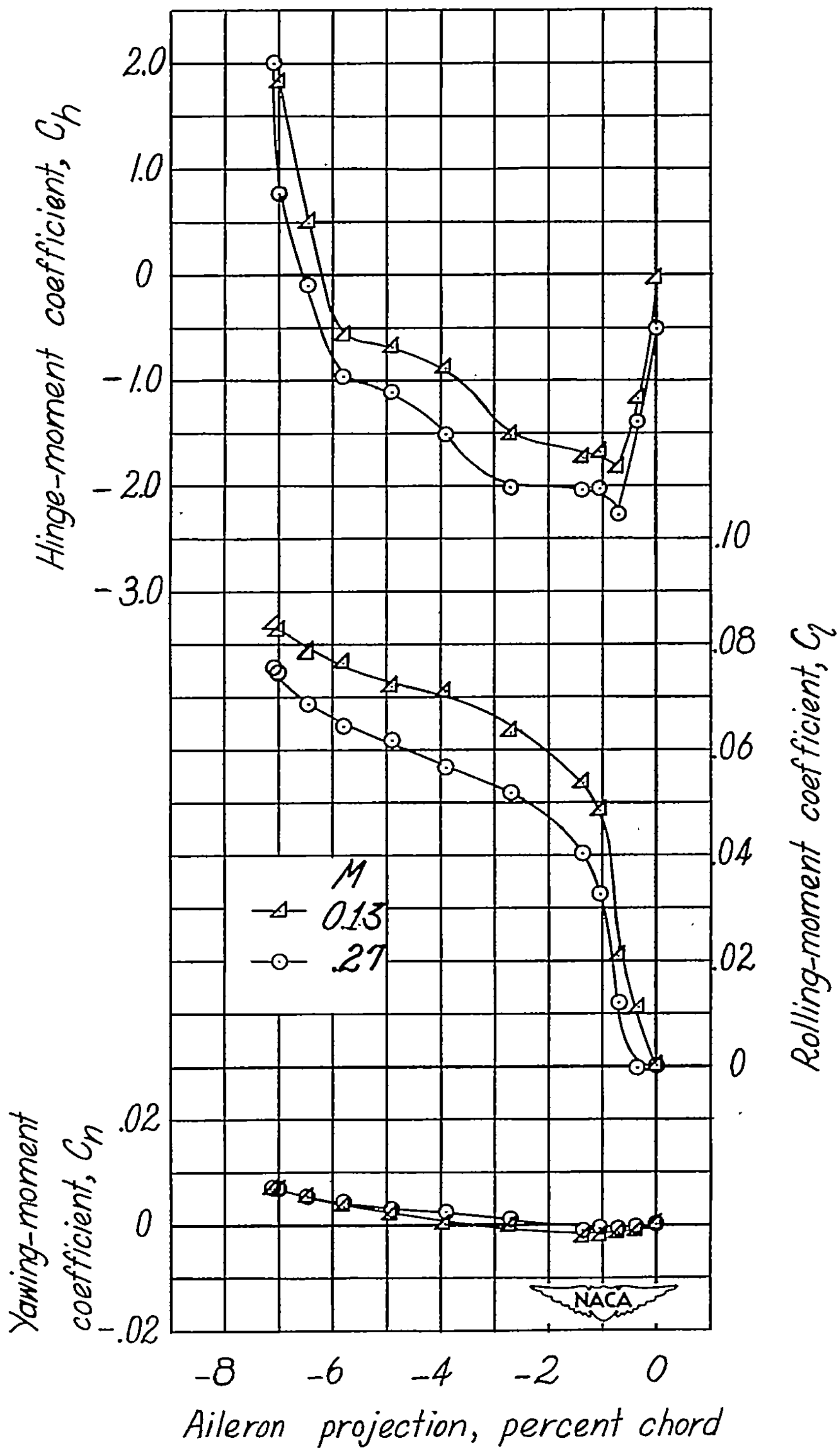
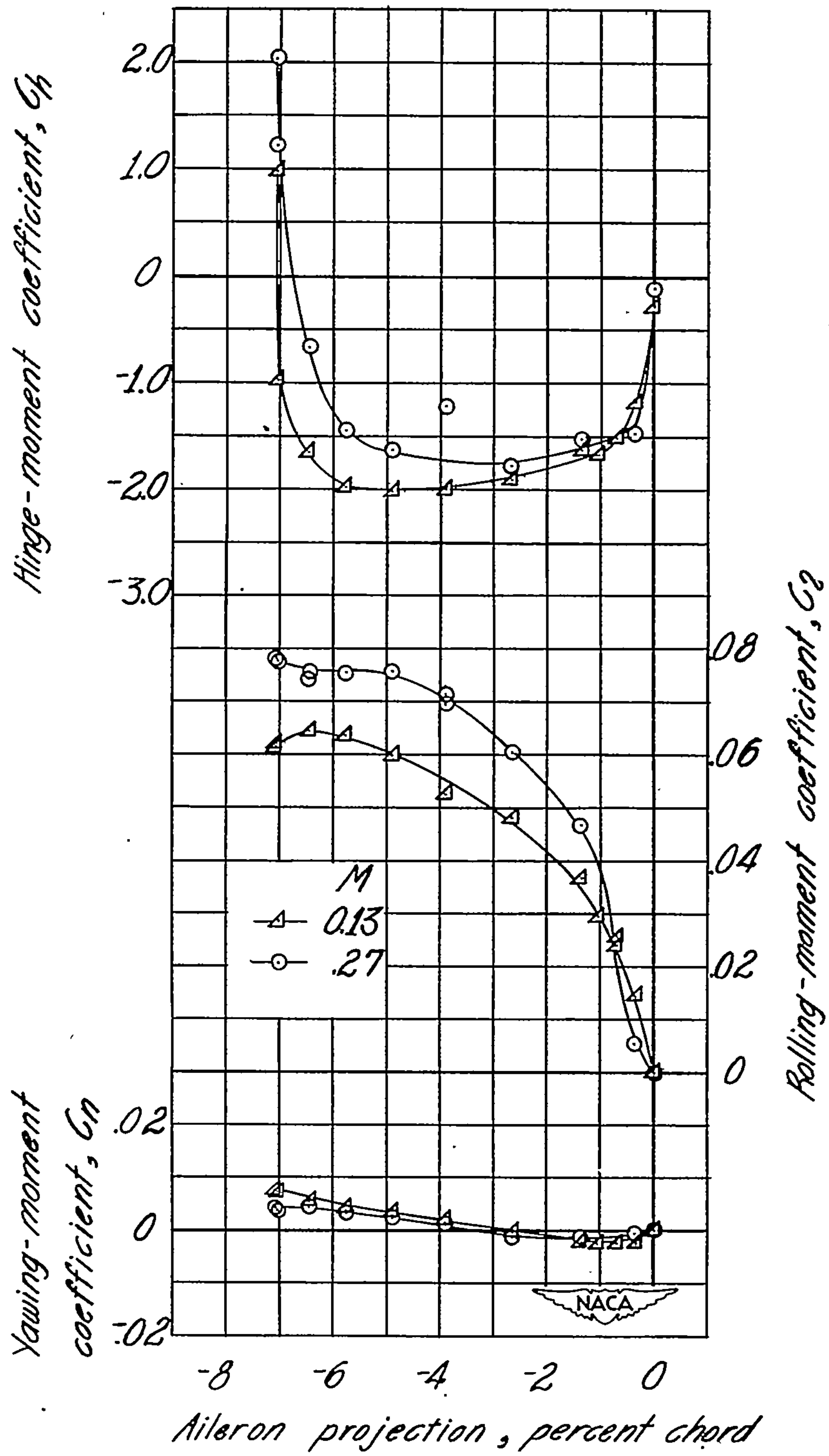



Figure 7.– Variation of lateral–control characteristics of complete wing with projection of thin–plate circular plug aileron at various angles of attack. Flap retracted. M = 0.27.



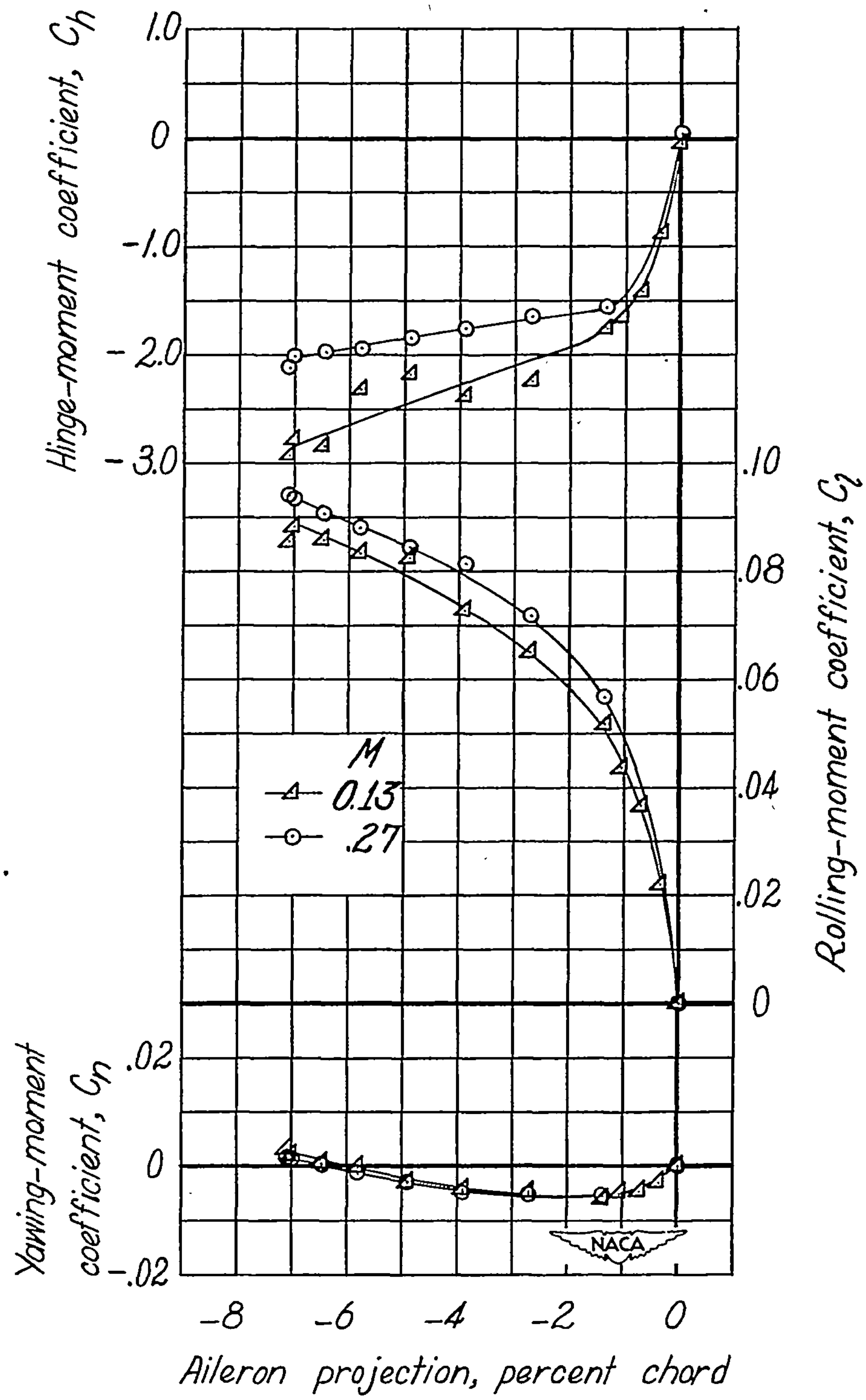

(a) $\alpha \approx -1.6^{\circ}$; $C_L \approx 1.38$.

Figure 8.– Variation of lateral-control characteristics of complete wing with projection of thin-plate circular plug aileron at various Mach numbers. Flap deflected 45°.




(b) $\alpha \approx 2.7^{\circ}$; $C_L \approx 1.56$.

Figure 8.– Continued.




(c) $\alpha \approx 7.2^\circ$; $C_L \approx 1.87$.

Figure 8.– Concluded.

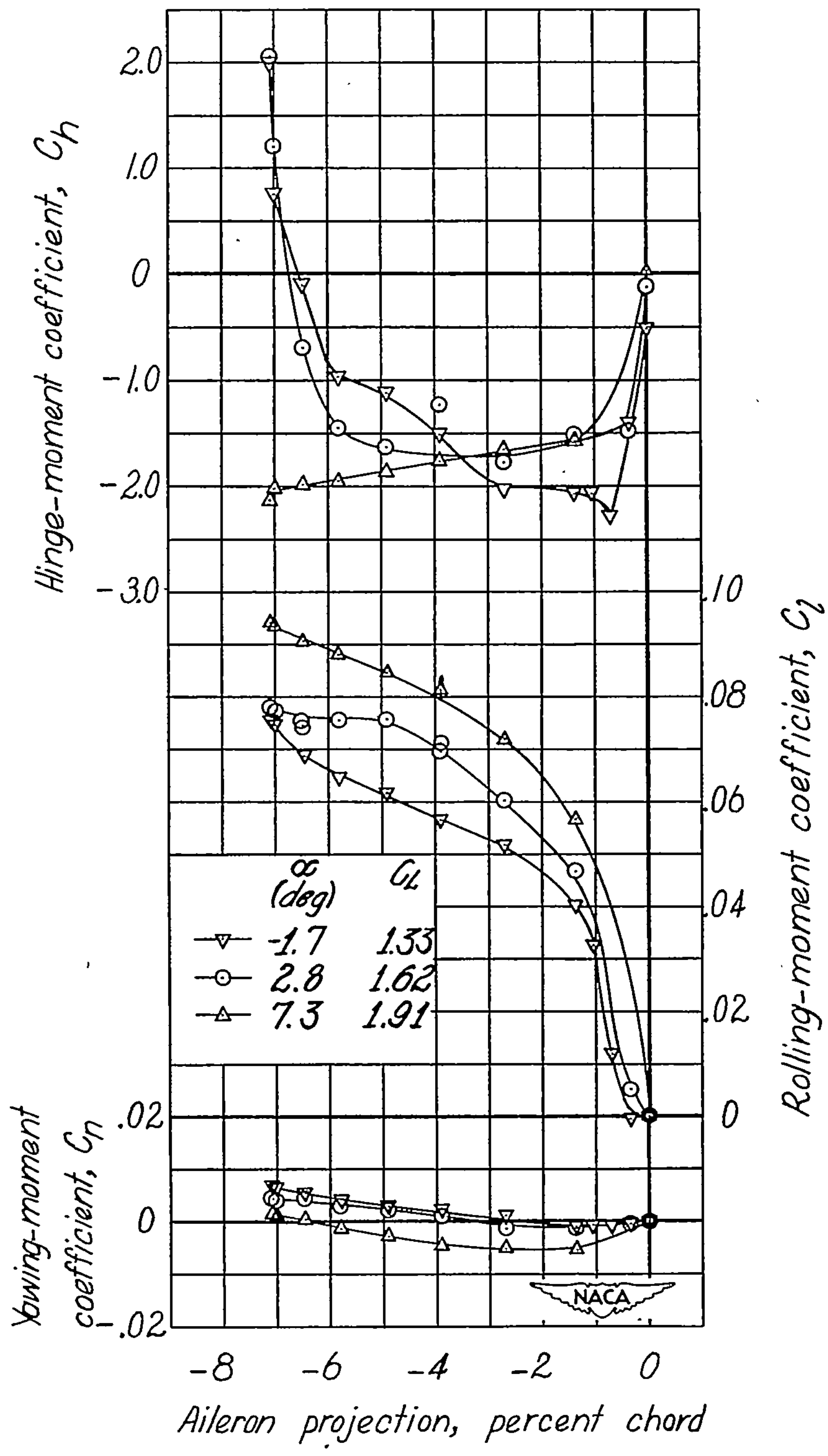
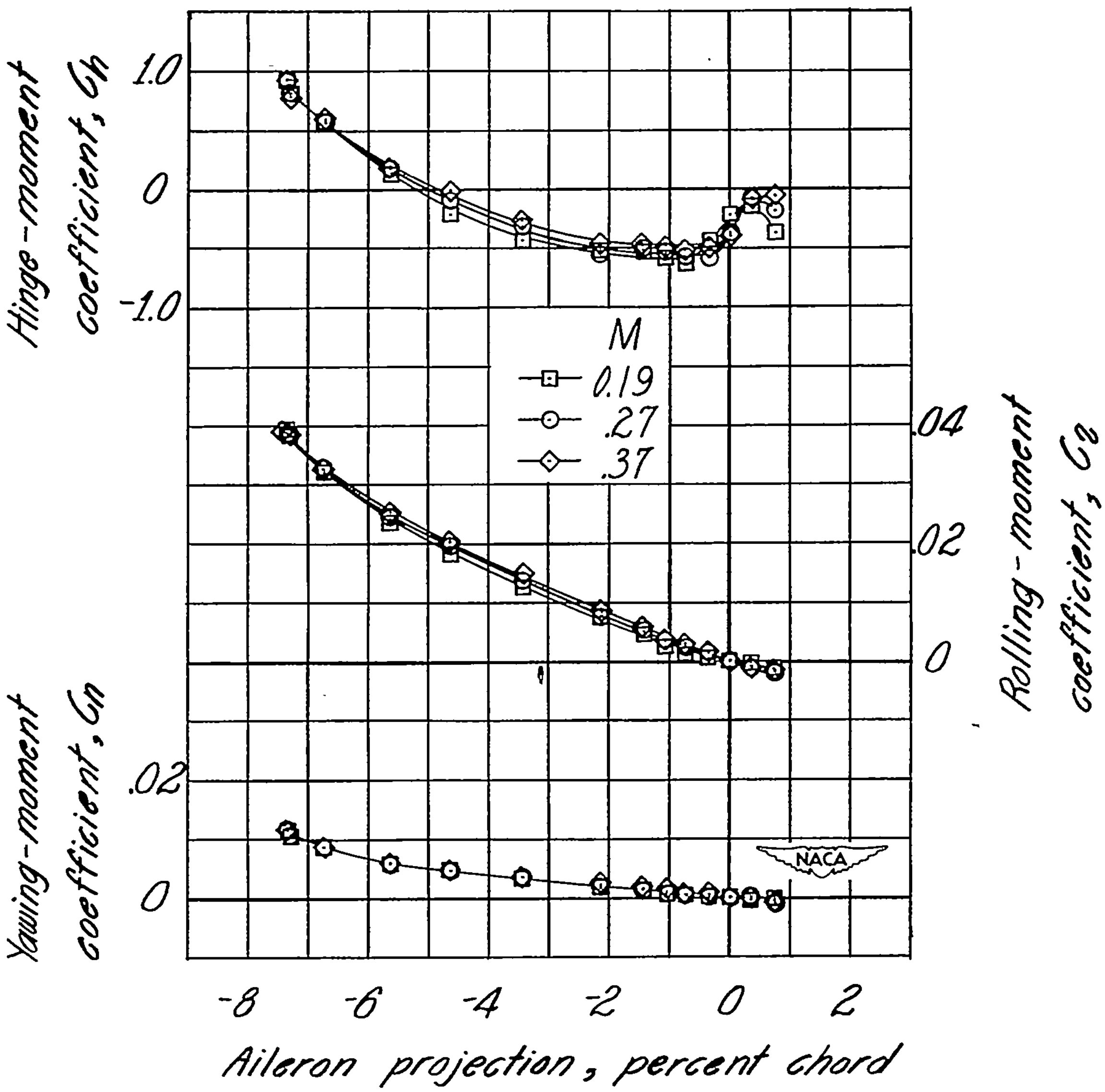
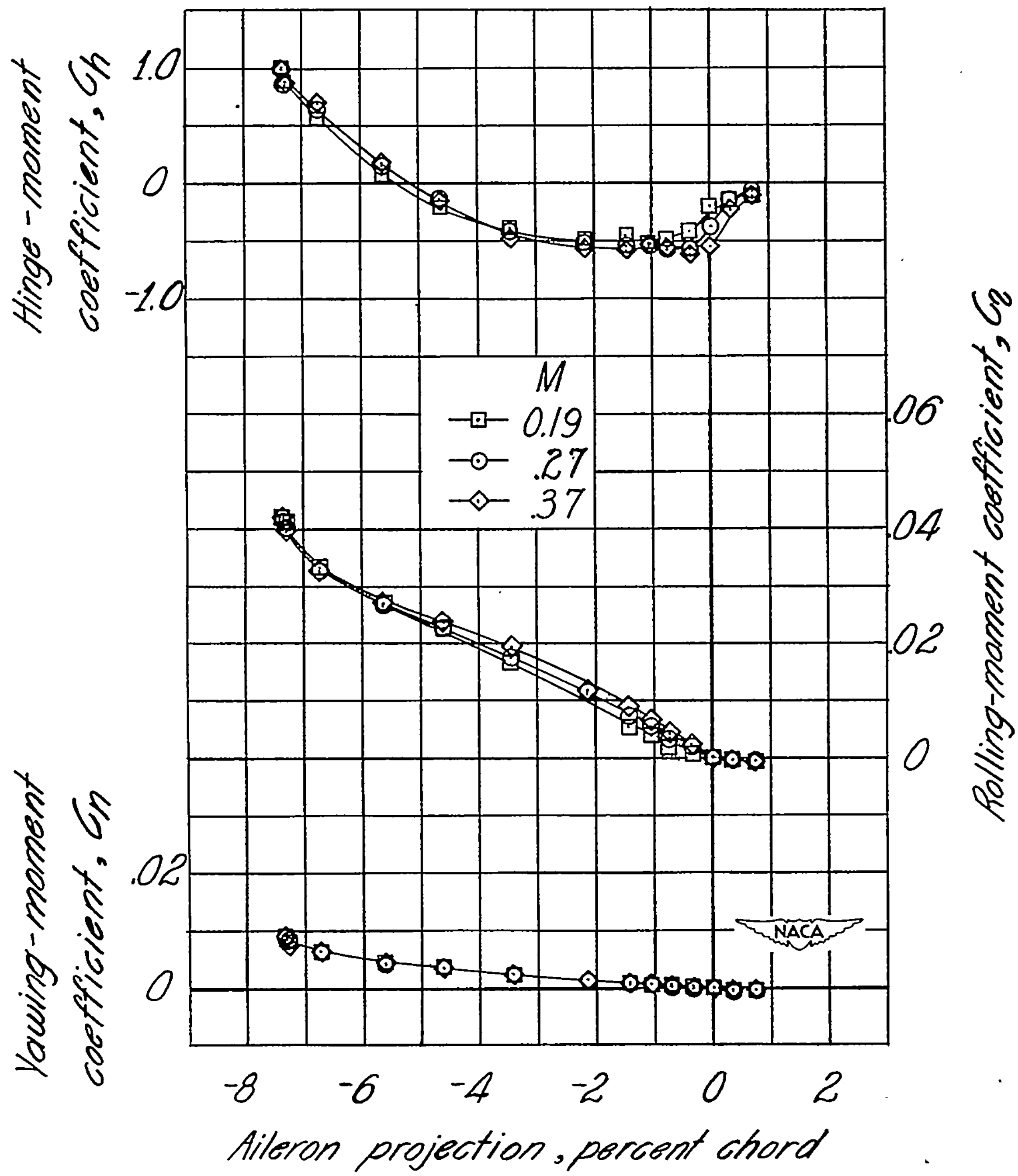



Figure 9.– Variation of lateral–control characteristics of complete wing with projection of thin–plate circular plug aileron at various angles of attack. Flap deflected 45°. M = 0.27.



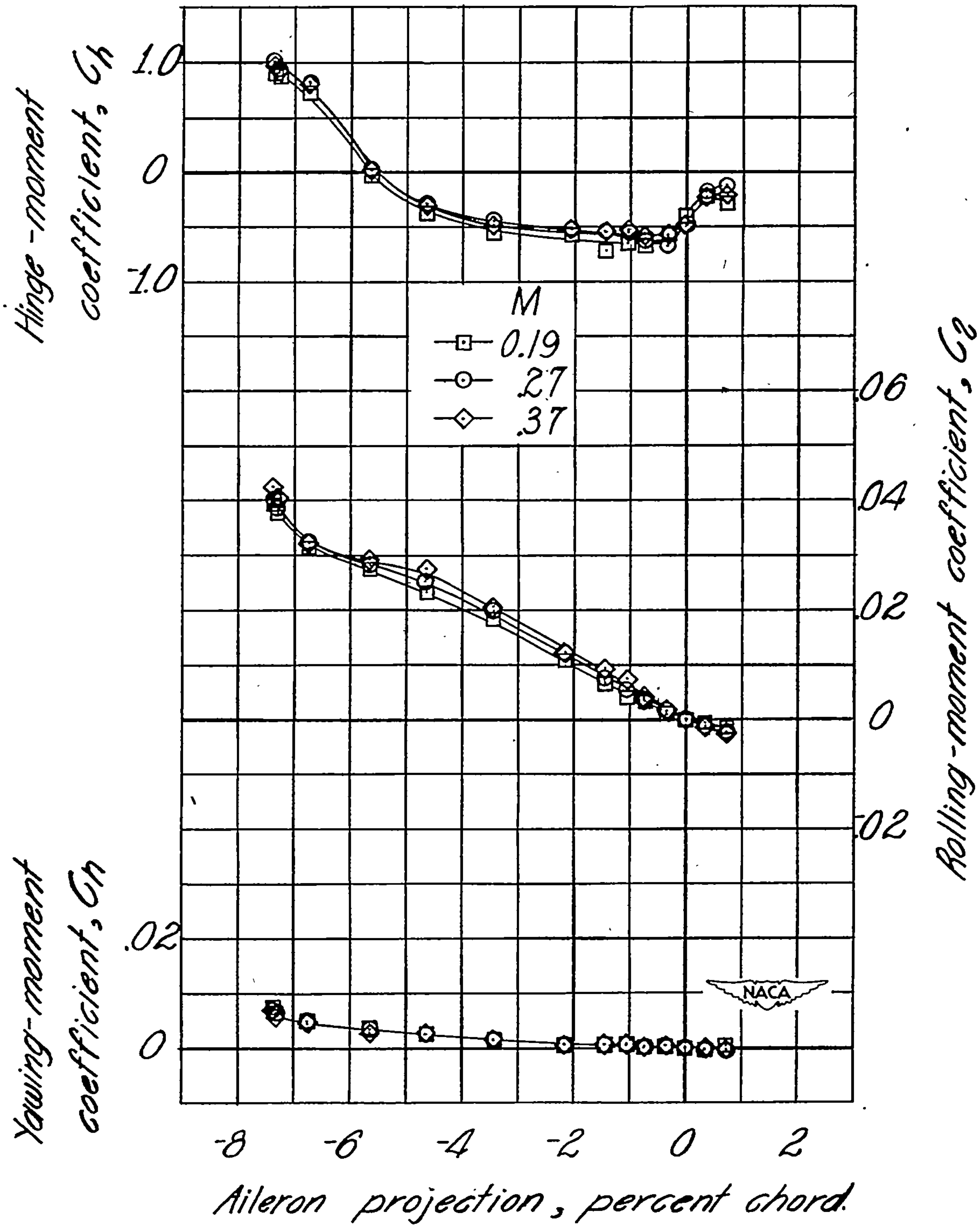

(a) $\alpha \approx 0.2^{\circ}$; $C_L \approx 0.11$.

Figure 10.– Variation of lateral-control characteristics of complete wing with projection of double-walled circular plug aileron at various Mach numbers. Flap retracted.



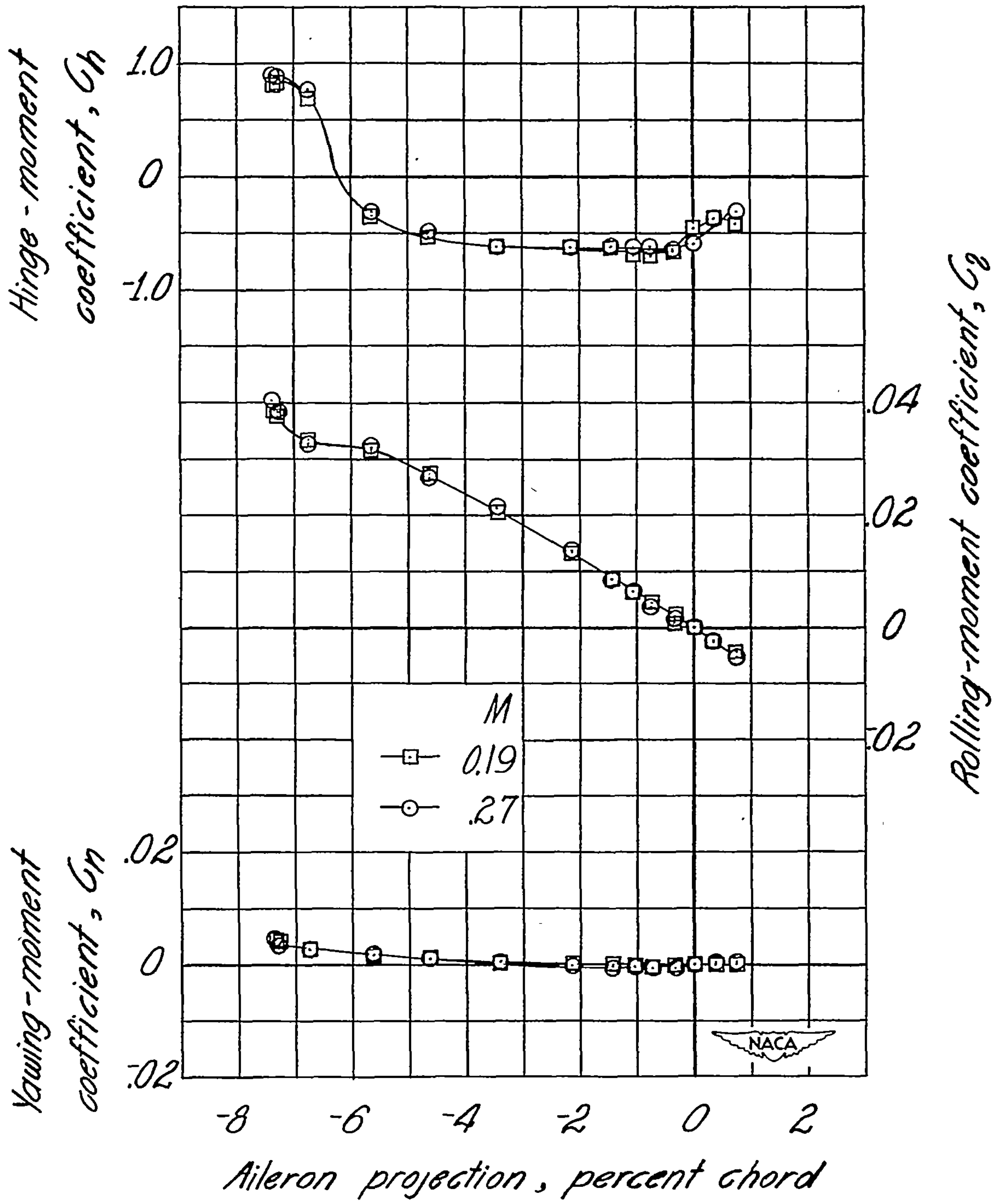

(b) $\alpha \approx 4.7^{\circ}$; $C_L \approx 0.44$.

Figure 10.– Continued.



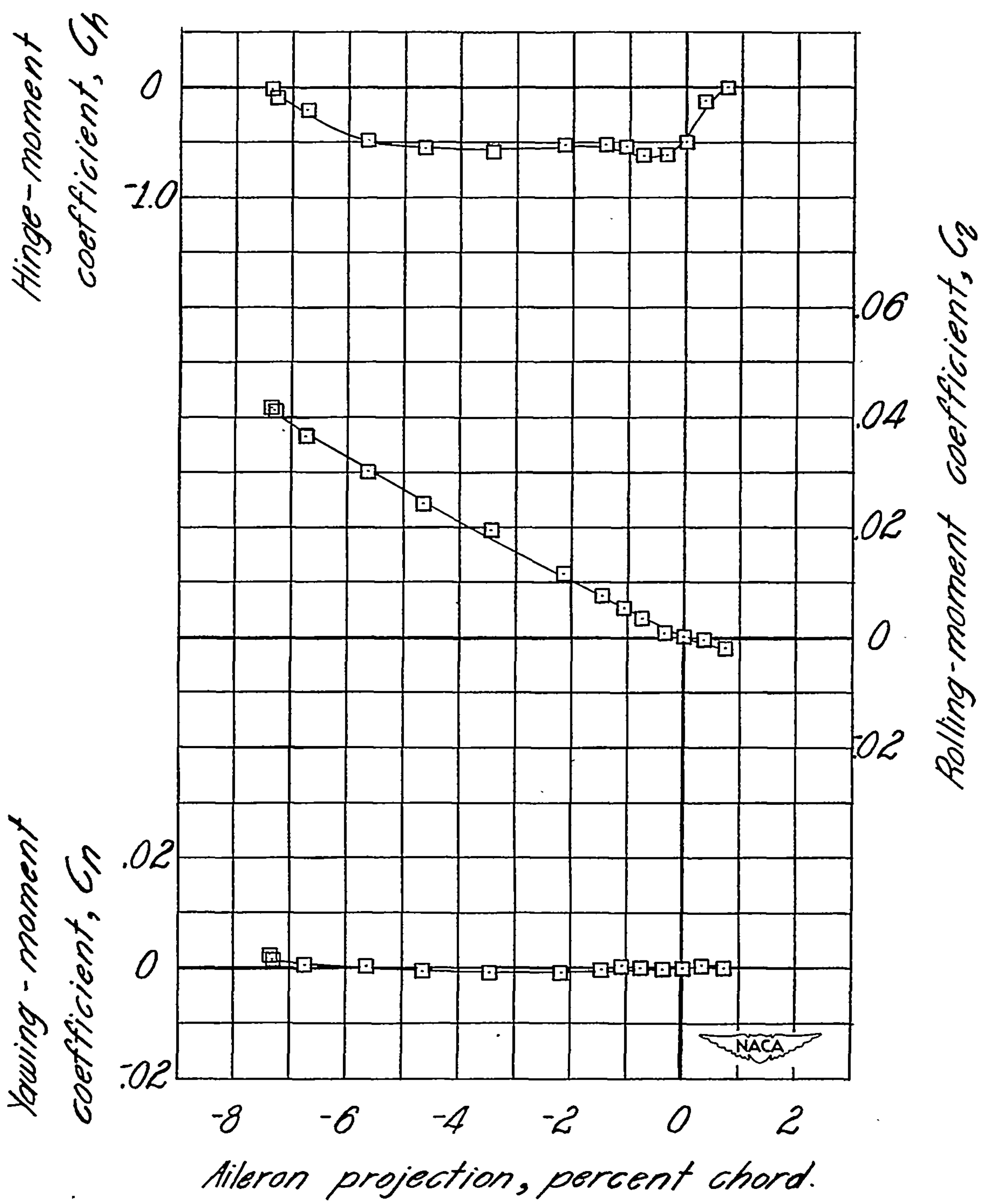

(c) $\alpha \approx 8.1^{\circ}$; $C_L \approx 0.70$.

Figure 10.— Continued.




(d) $\alpha \approx 11.5^{\circ}$; $C_L \approx 0.91$.

Figure 10.– Continued.




(e) $\alpha = 14.8^{\circ}$; $C_L = 1.13$; $M = 0.19$.

Figure 10.– Concluded.

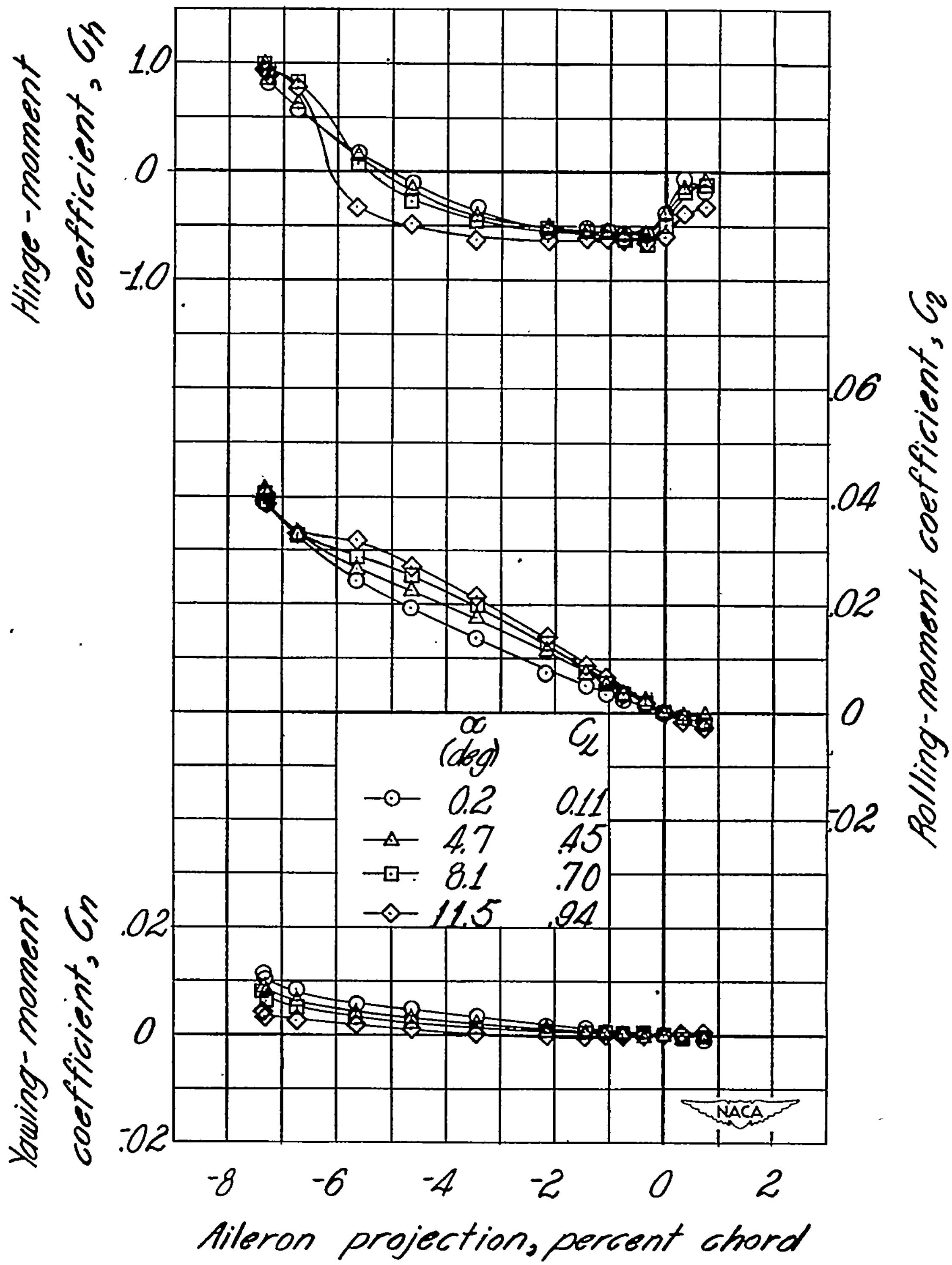
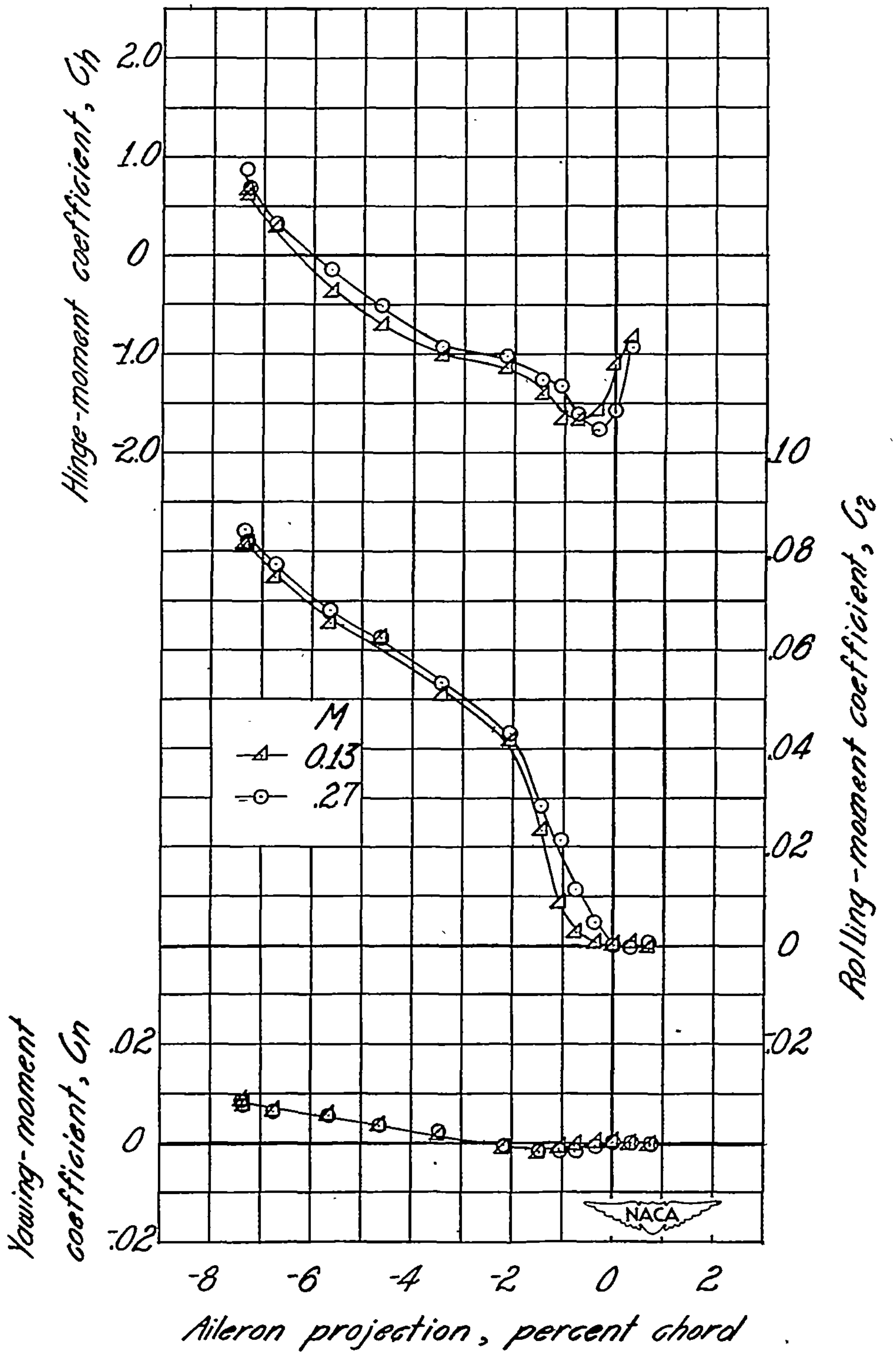
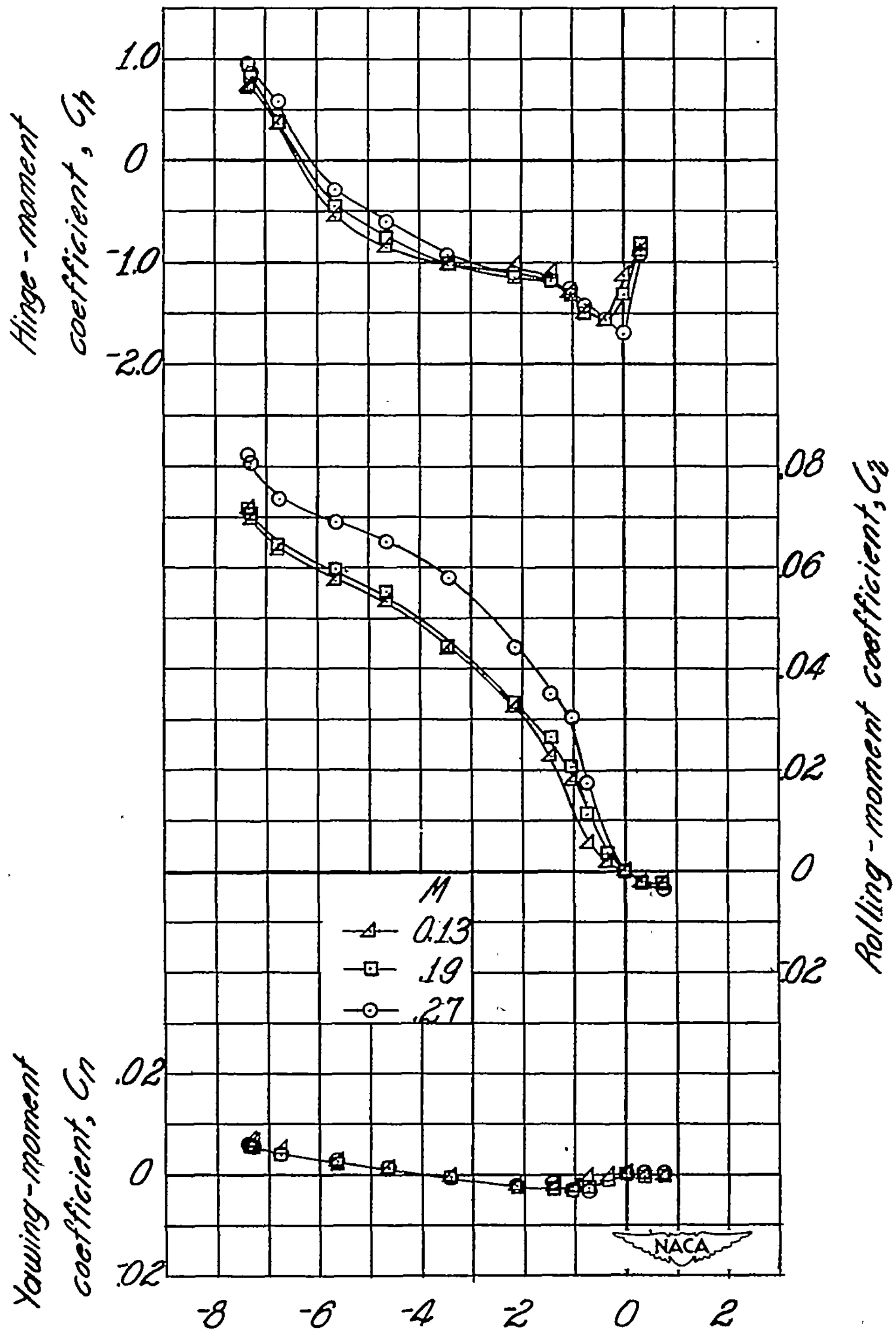



Figure 11.- Variation of lateral-control characteristics of complete wing with projection of double-walled circular plug aileron at various angles of attack. Flap retracted. M = 0.27.



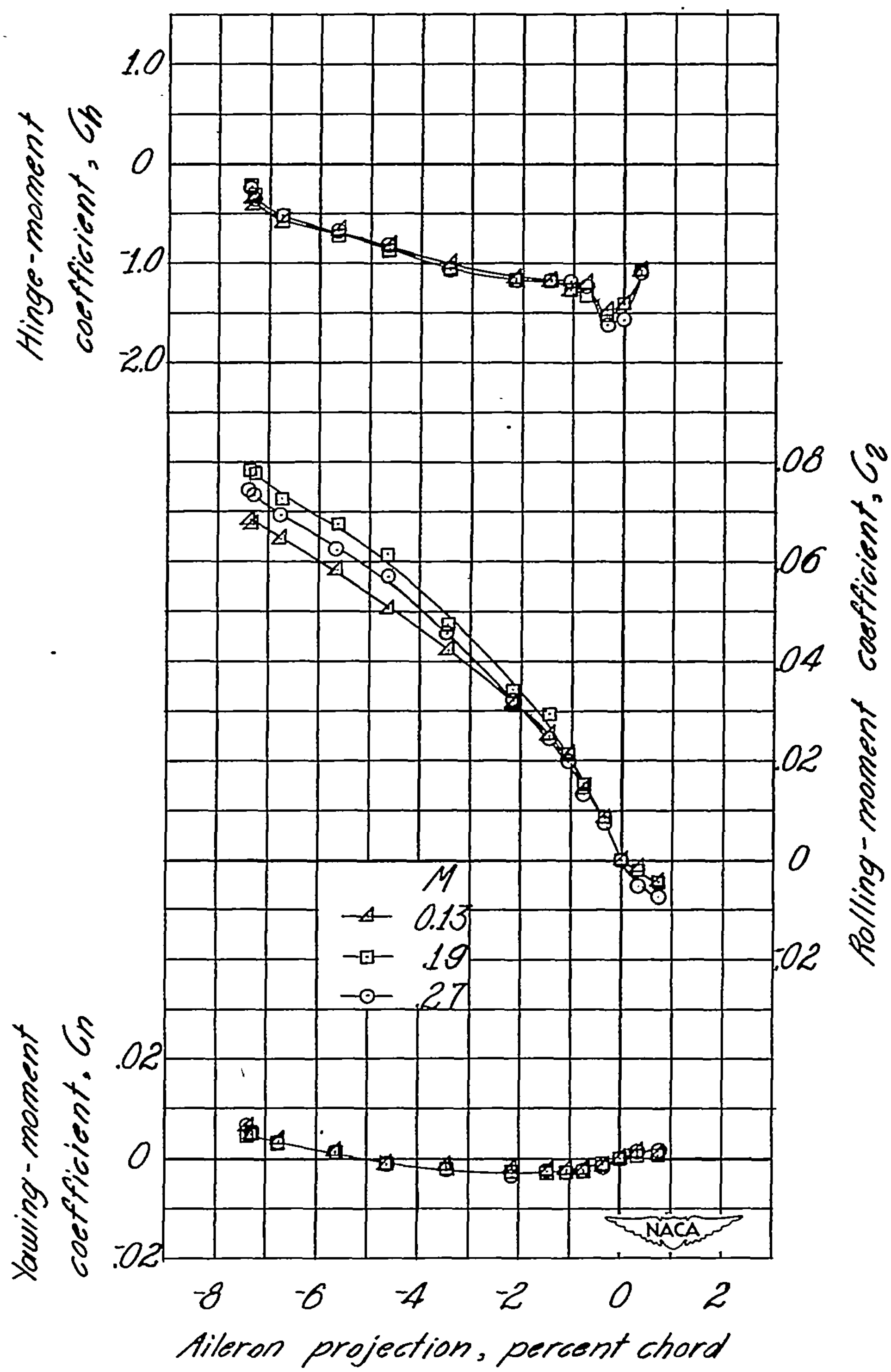

(a) $\alpha \approx -1.9^\circ$; $C_L \approx 1.31$.

Figure 12.— Variation of lateral-control characteristics of complete wing with projection of double-walled circular plug aileron at various Mach numbers. Flap deflected $45^\circ$.



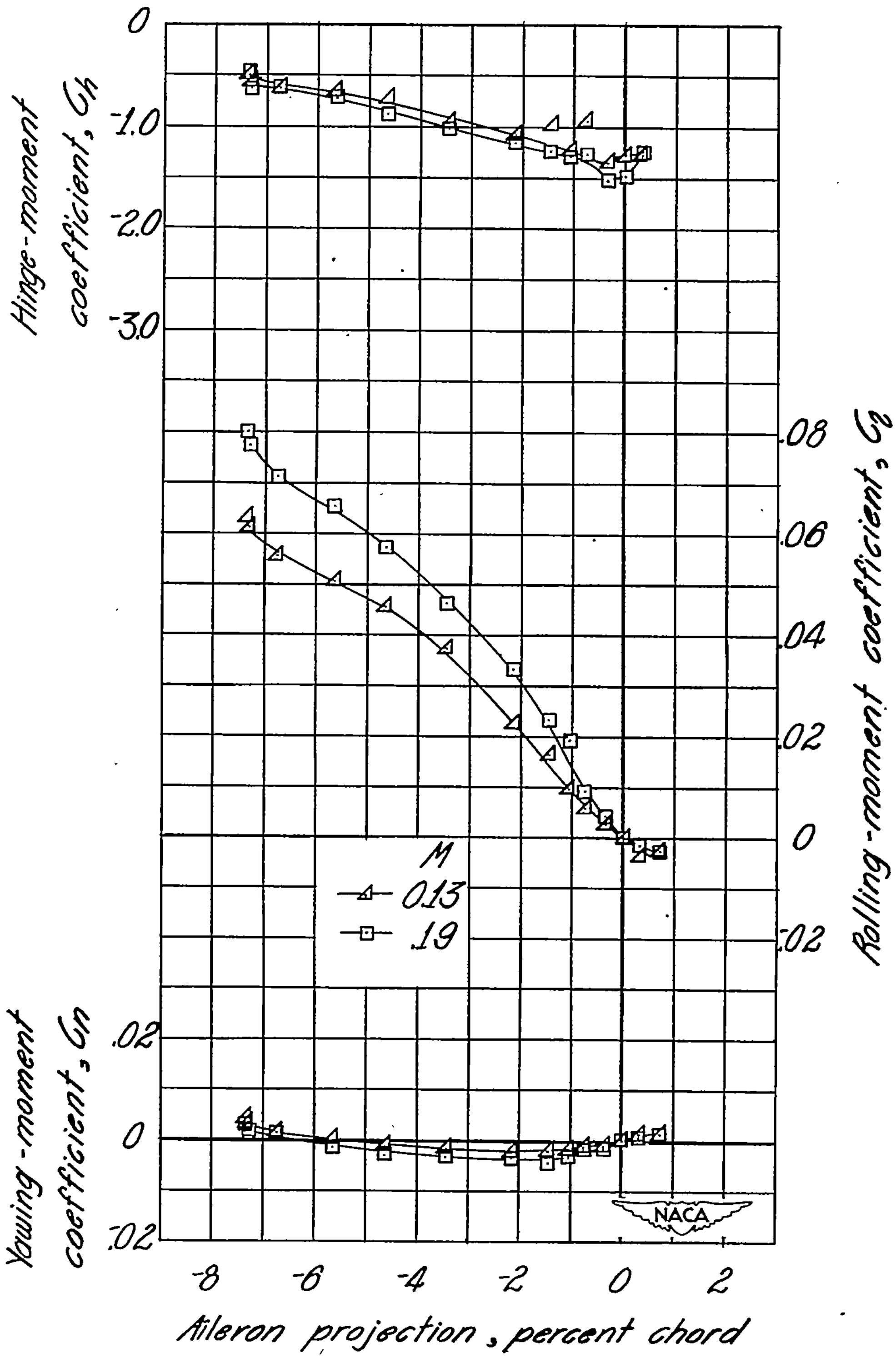

(b) $\alpha \approx 2.4^{\circ}$; $C_L \approx 1.52$.

Figure 12.– Continued.




(c) $\alpha \approx 6.8^{\circ}$; $C_L \approx 1.75$.

Figure 12.— Continued.




(d) $\alpha \approx 10.0^{\circ}$; $C_L \approx 1.88$.

Figure 12.– Concluded.

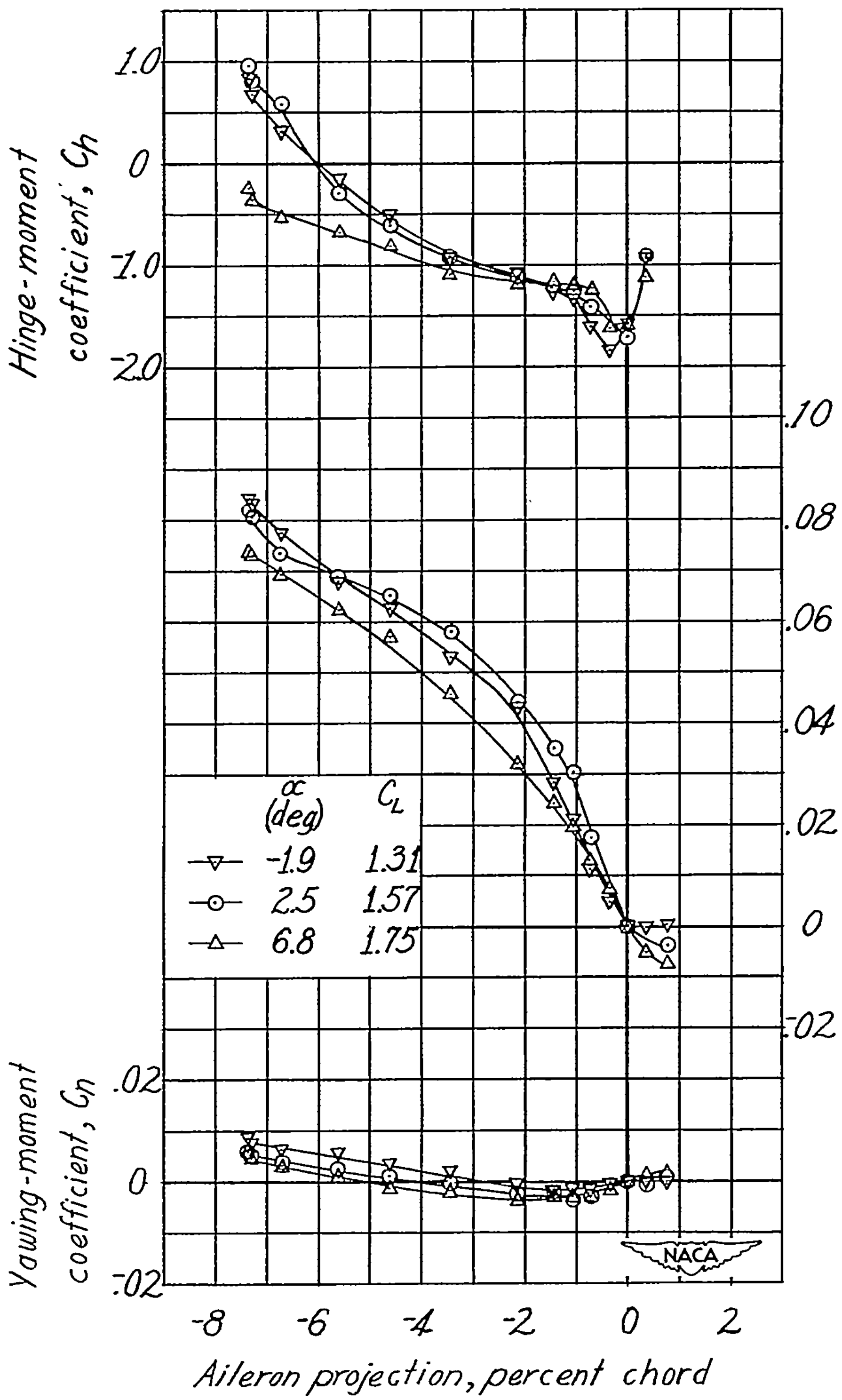
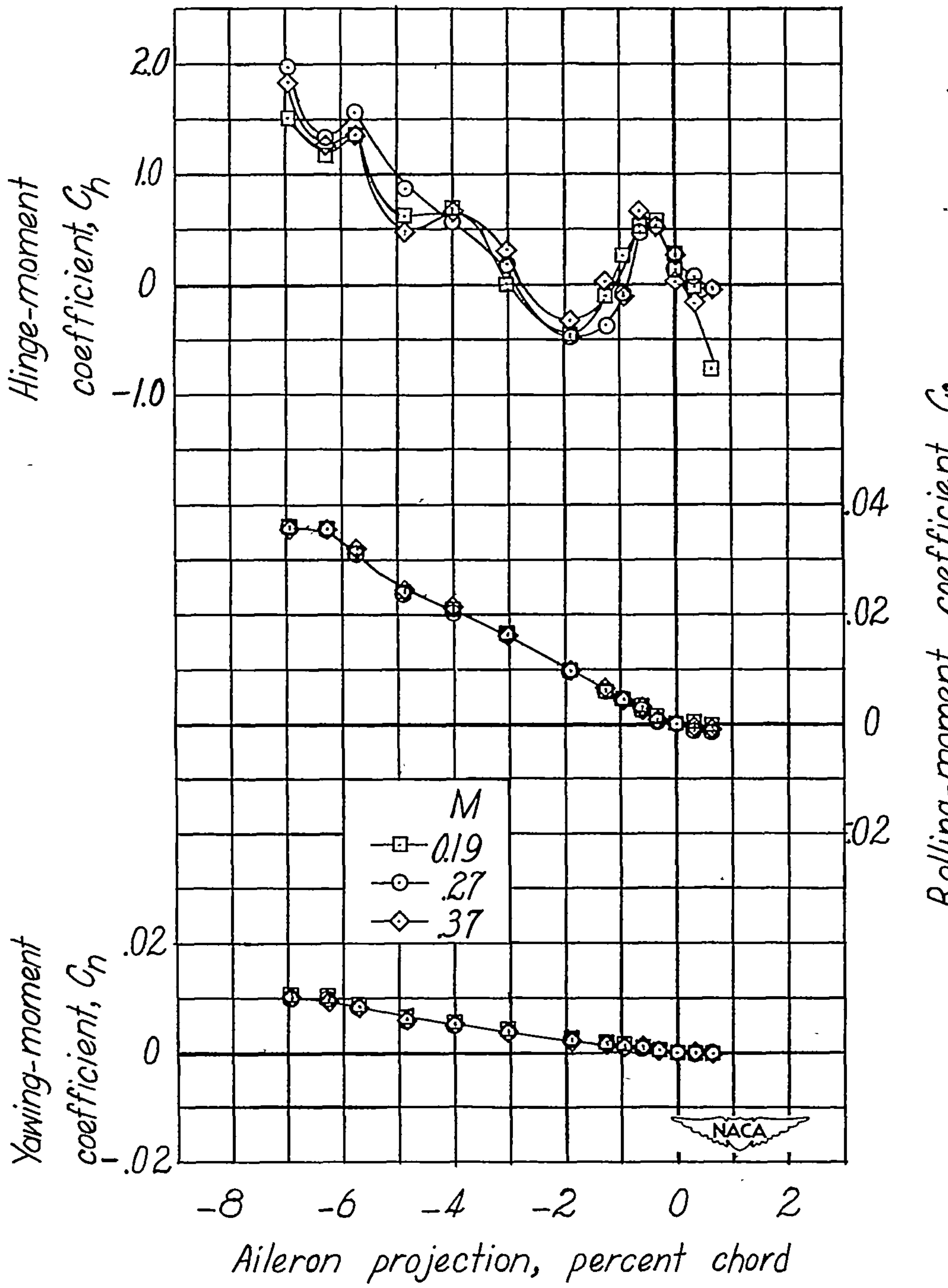
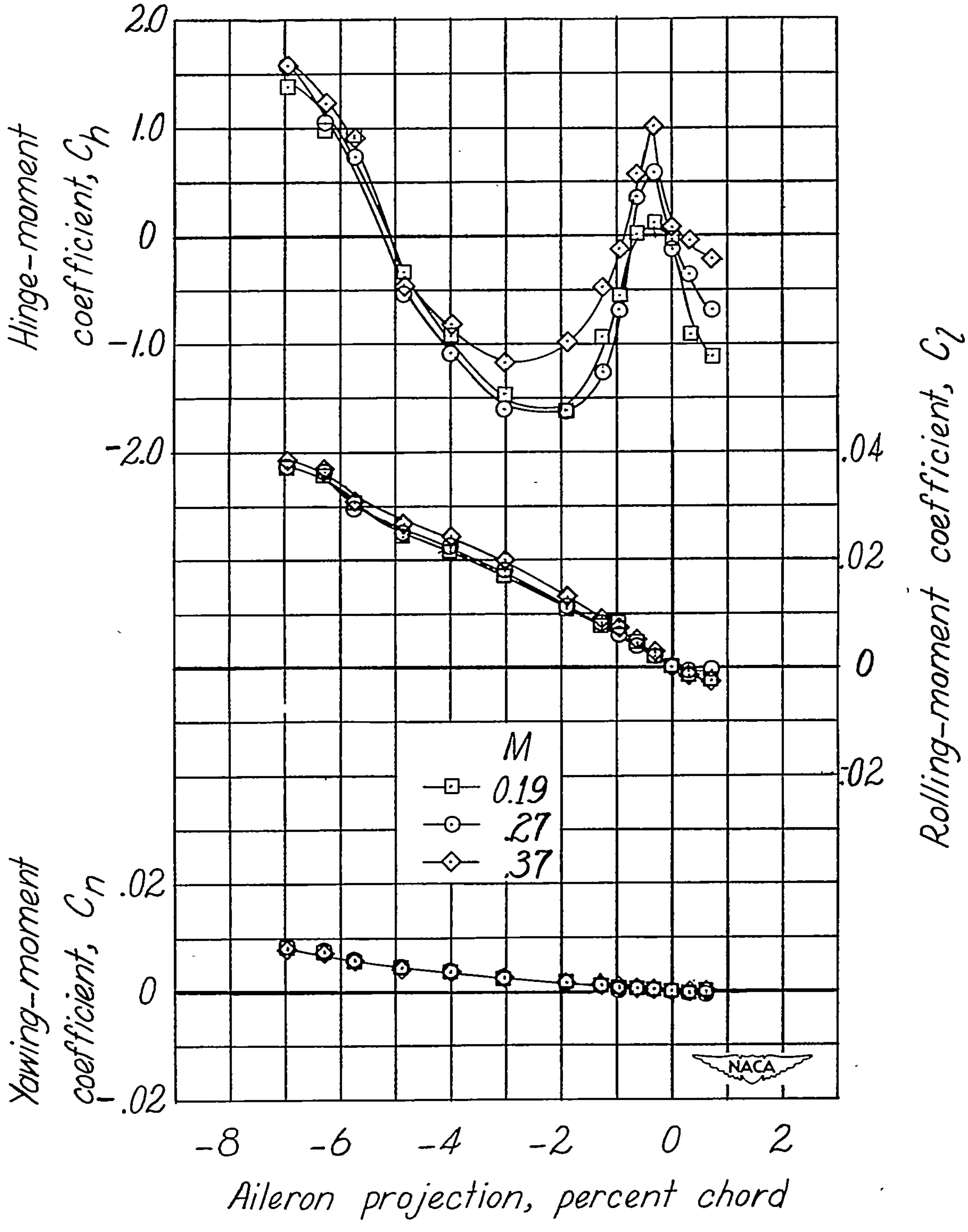



Figure 13.– Variation of lateral-control characteristics of complete wing with projection of double-walled circular plug aileron at various angles of attack. Flap deflected 45°. M = 0.27.



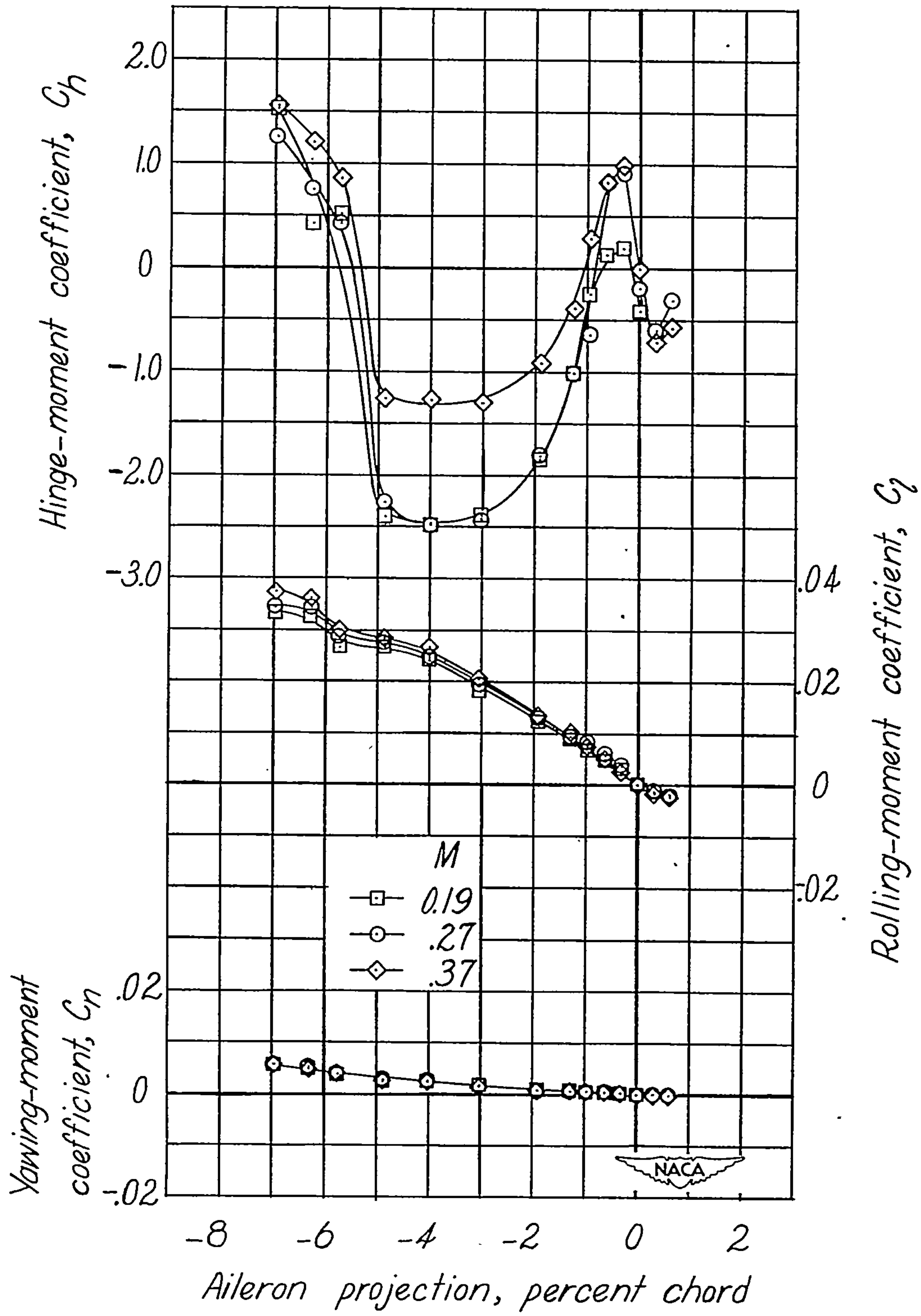

(a) $\alpha \approx 0.2^{\circ}$; $C_L \approx 0.13$.

Figure 14.– Variation of lateral-control characteristics of complete wing with projection of modified double-walled circular plug aileron at various Mach numbers. Plug aileron modified by removing 0.015c top plate. Flap retracted.



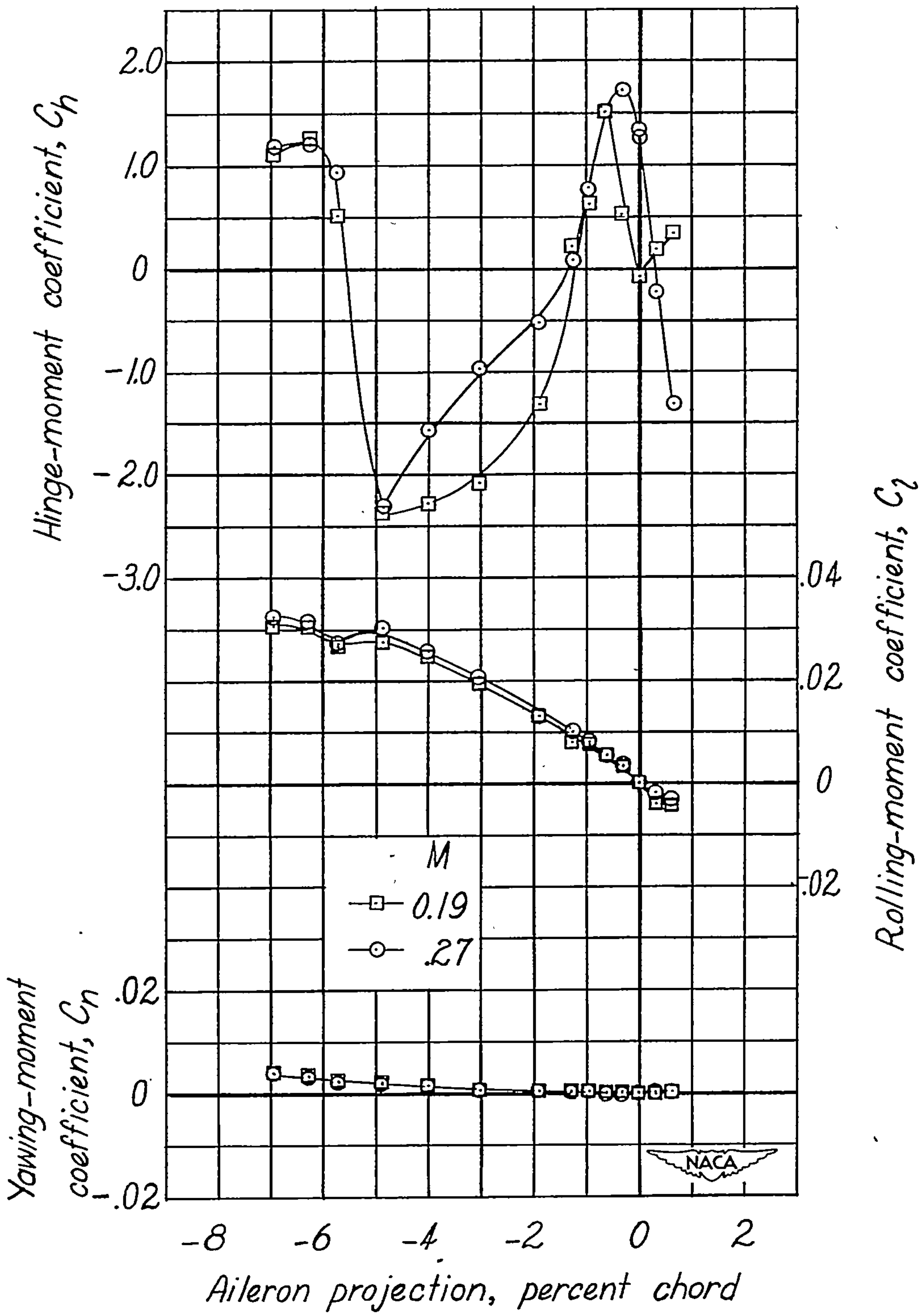

(b) $\alpha \approx 4.7^{\circ}$; $C_L \approx 0.47$.

Figure 14.– Continued.



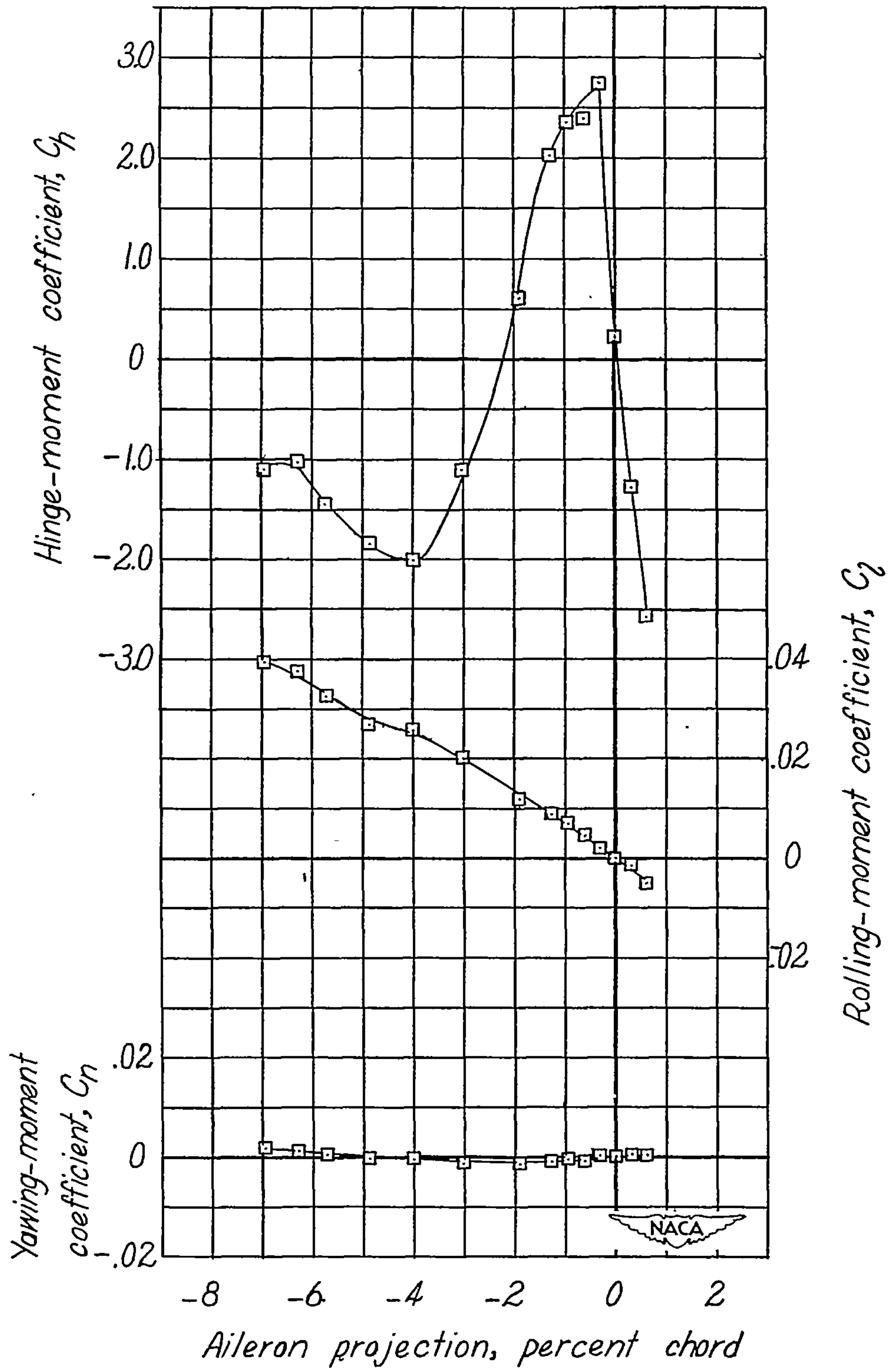

(c) $\alpha \approx 8.1°$; $C_L \approx 0.71$.

Figure 14.– Continued.




(d) $\alpha \approx 11.5^{\circ}$; $C_L \approx 0.94$.

Figure 14.– Continued.




(e) $\alpha = 14.8^{\circ}$; $C_L = 1.14$; $M = 0.19$.

Figure 14.– Concluded.

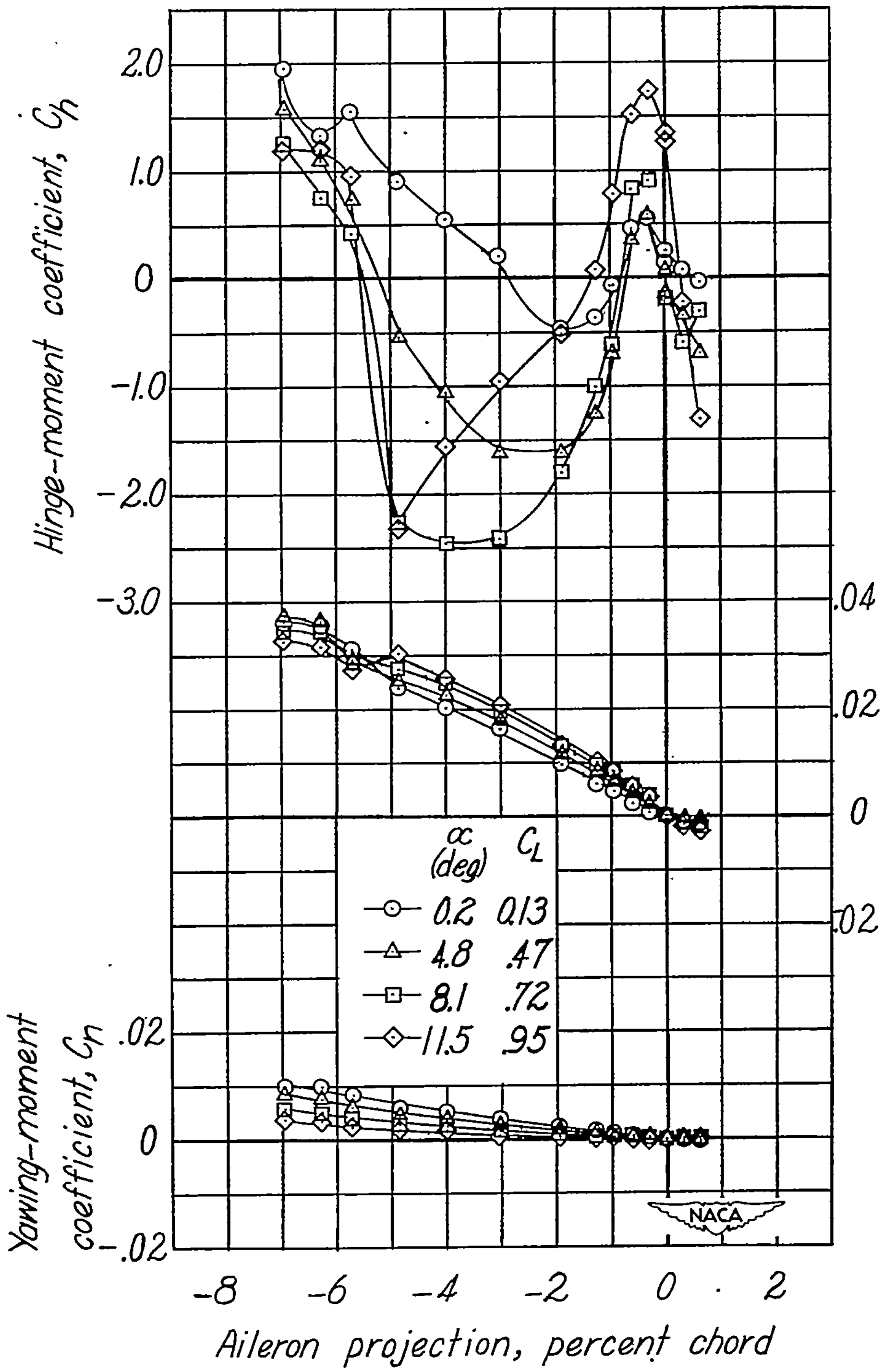
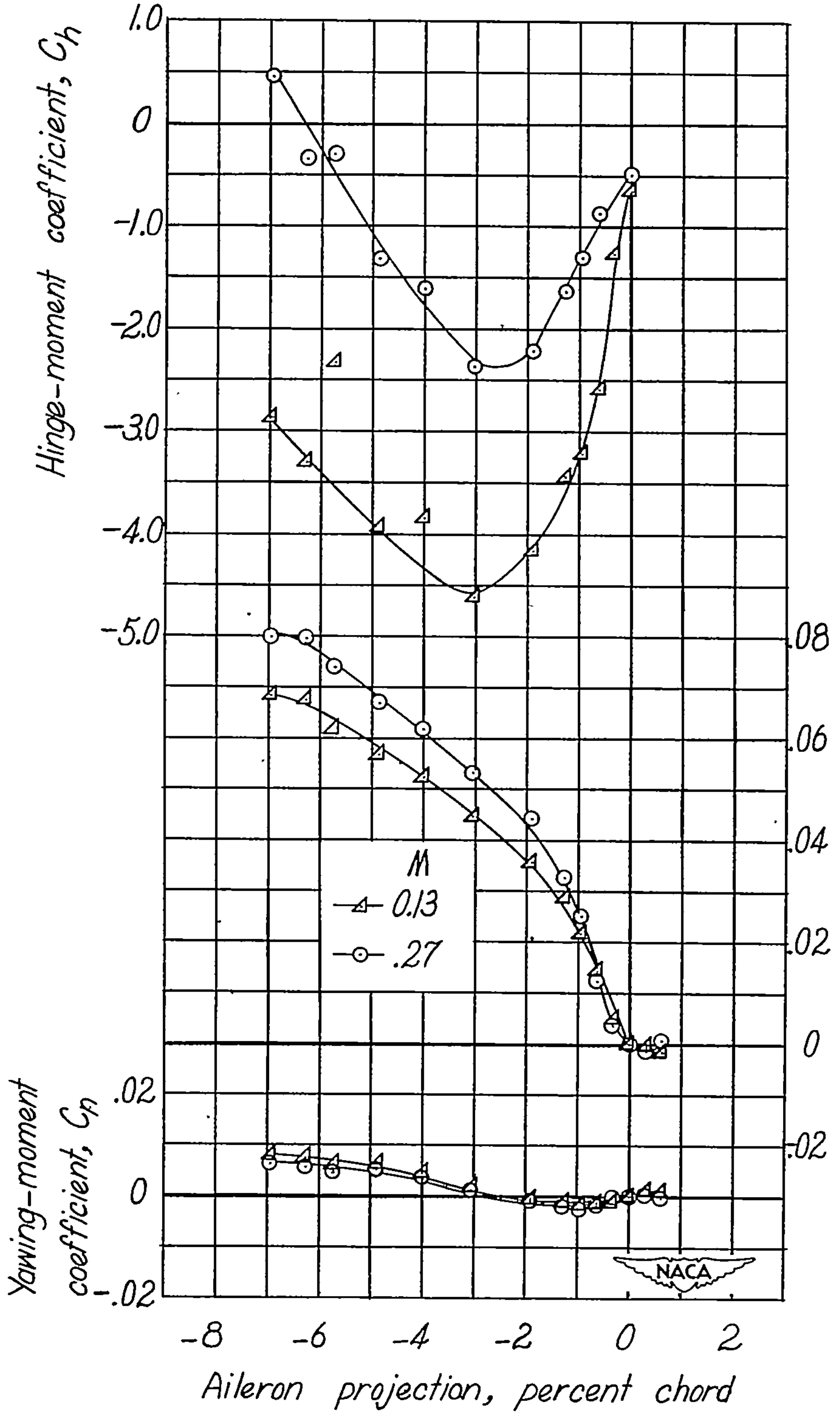
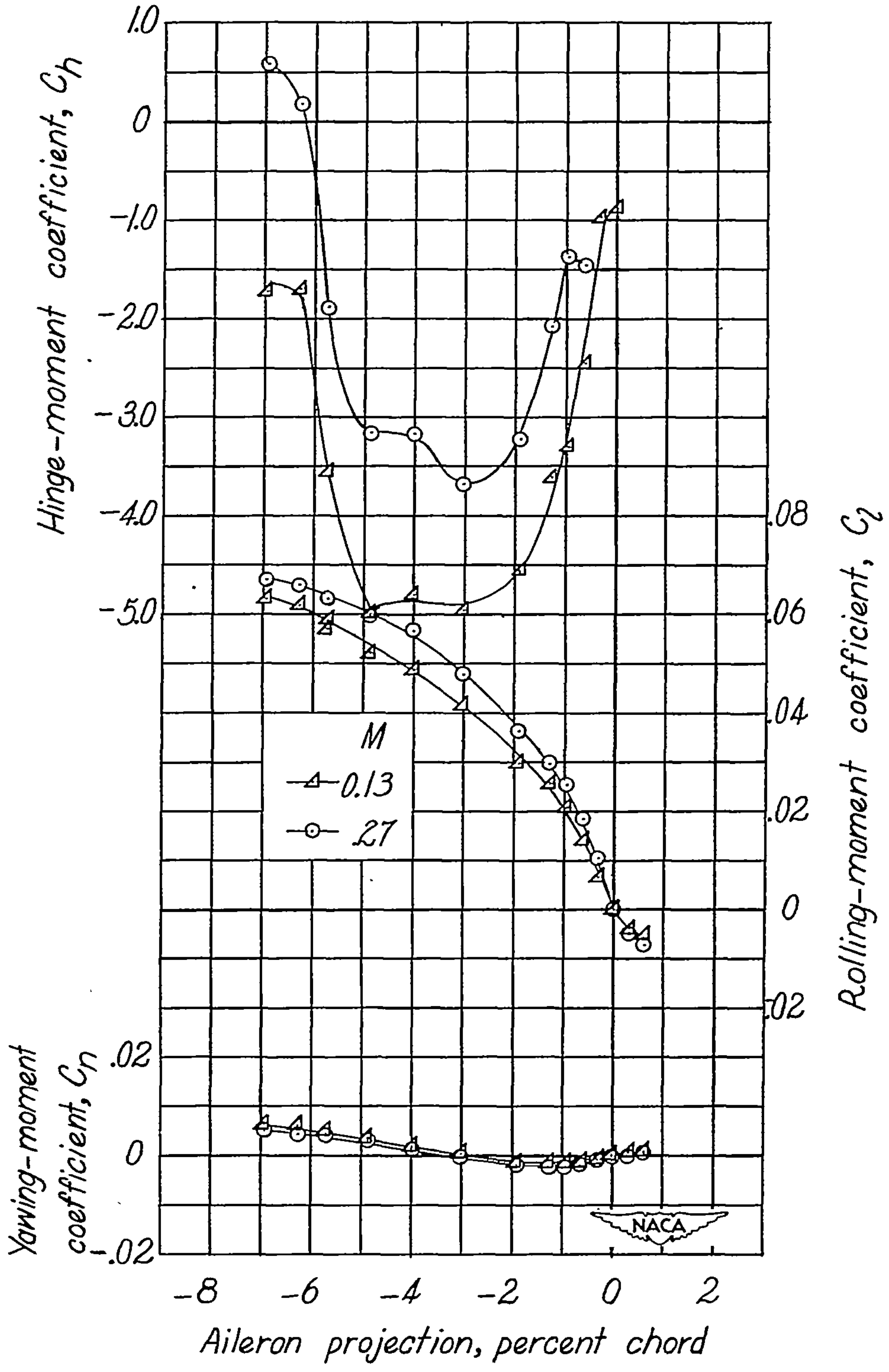



Figure 15.– Variation of lateral-control characteristics of complete wing with projection of modified double-walled circular plug aileron at various angles of attack. Plug aileron modified by removing 0.015c top plate. Flap retracted. M = 0.27.



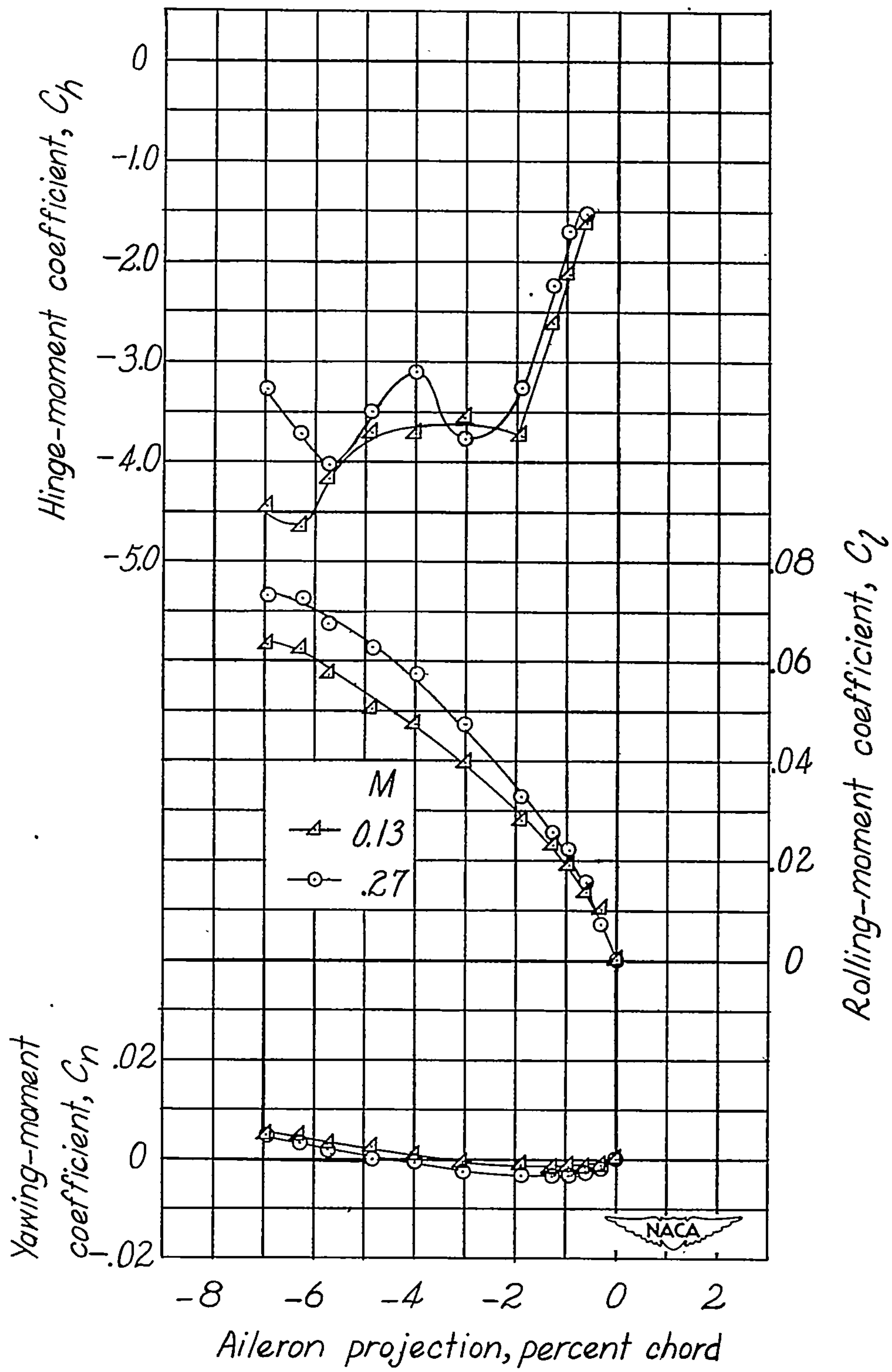

(a) $\alpha \approx -1.9^{\circ}$; $C_L \approx 1.31$.

Figure 16.– Variation of lateral-control characteristics of complete wing with projection of modified double-walled circular plug aileron at various Mach numbers. Plug aileron modified by removing 0.015c top plate. Flap deflected 45°.



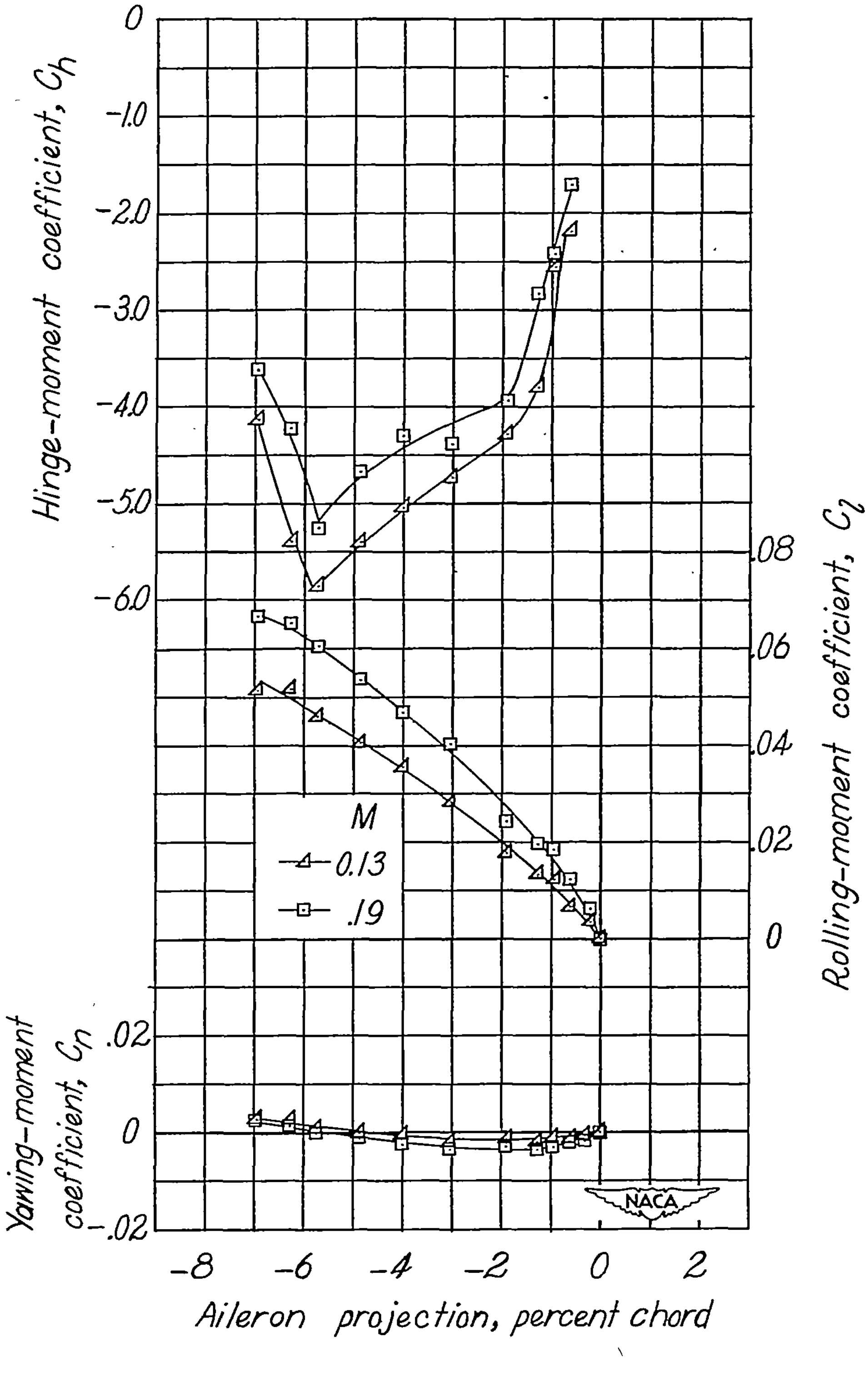

(b) $\alpha \approx 2.4^{\circ}$; $C_L \approx 1.50$.

Figure 16.– Continued.




(c) $\alpha \approx 6.8^{\circ}$; $C_L \approx 1.73$.

Figure 16.— Continued.




(d) $\alpha = 9.8^{\circ}$; $C_L = 1.81$.

Figure 16.– Concluded.

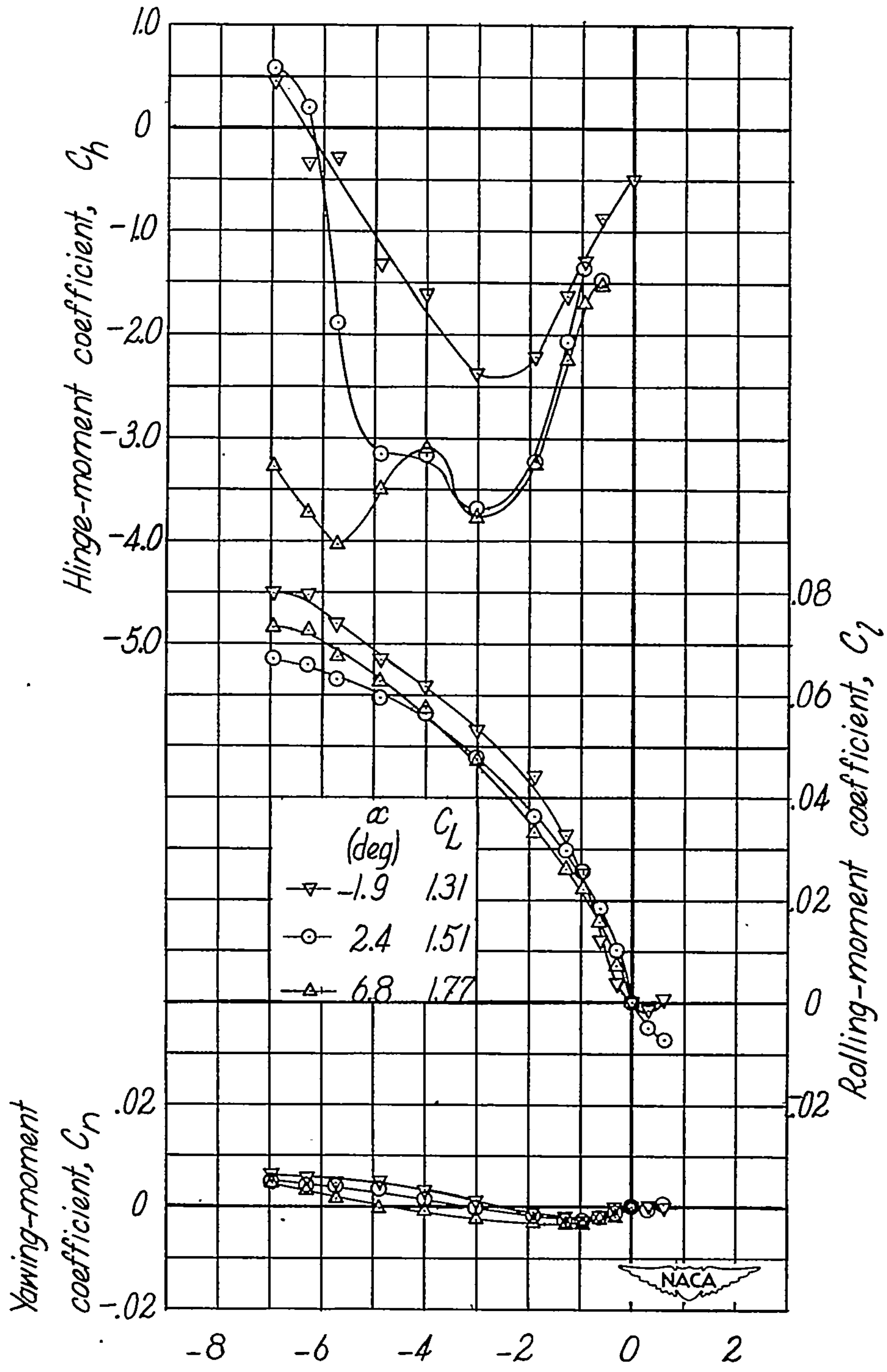
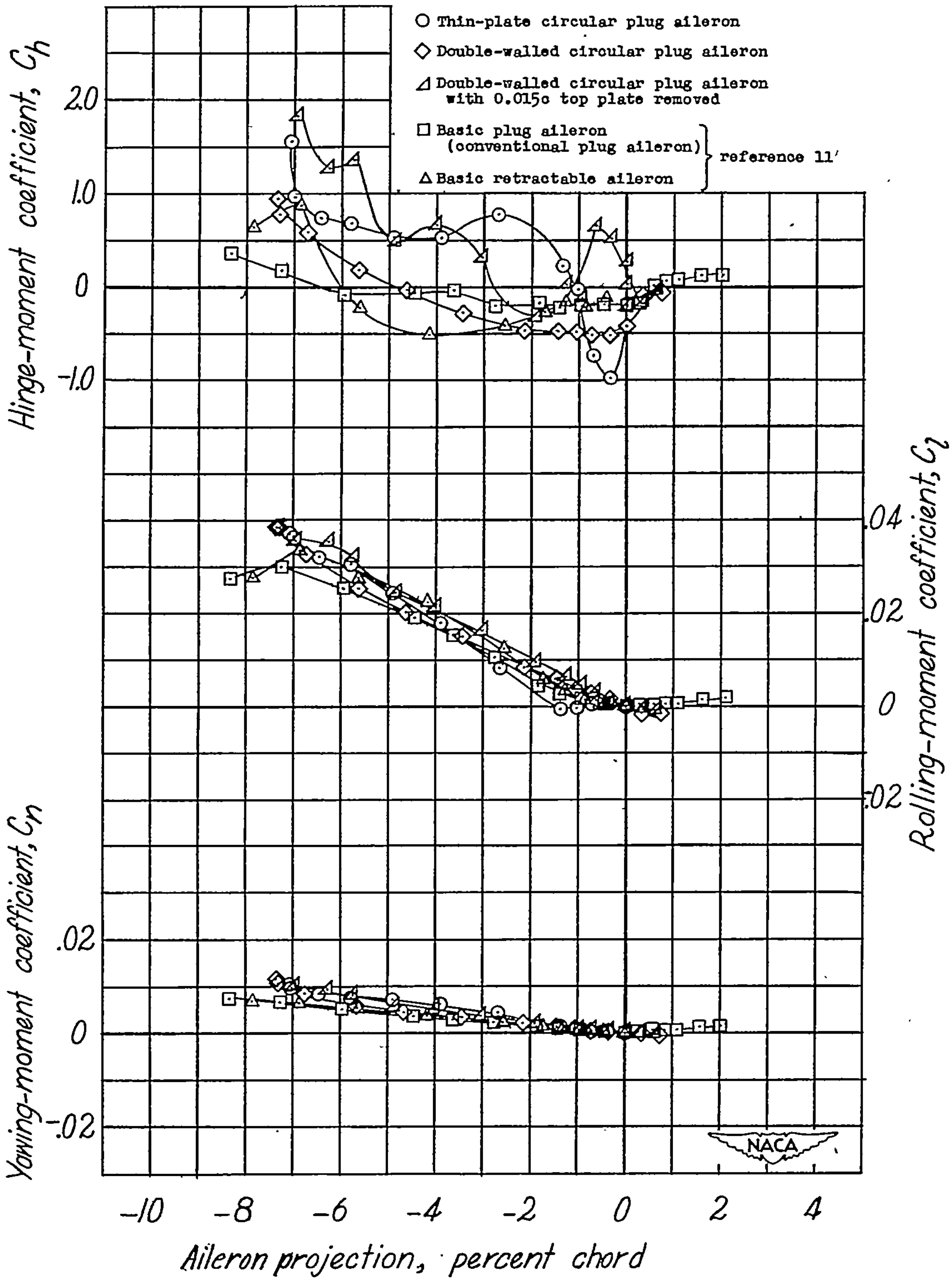
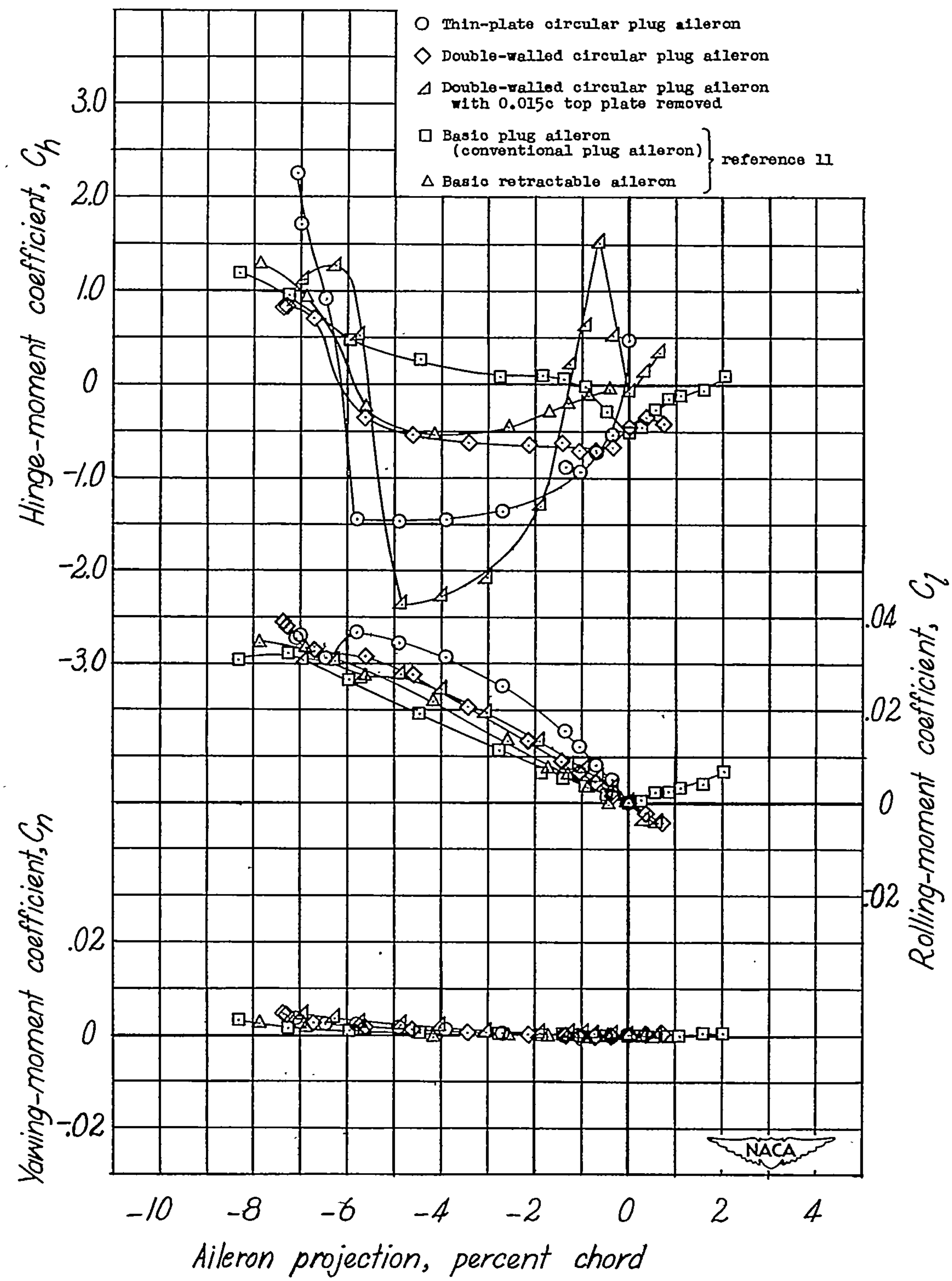



Figure 17.— Variation of lateral-control characteristics of complete wing with projection of modified double-walled circular plug aileron at various angles of attack. Plug aileron modified by removing 0.015c top plate. Flap deflected 45°. M = 0.27.



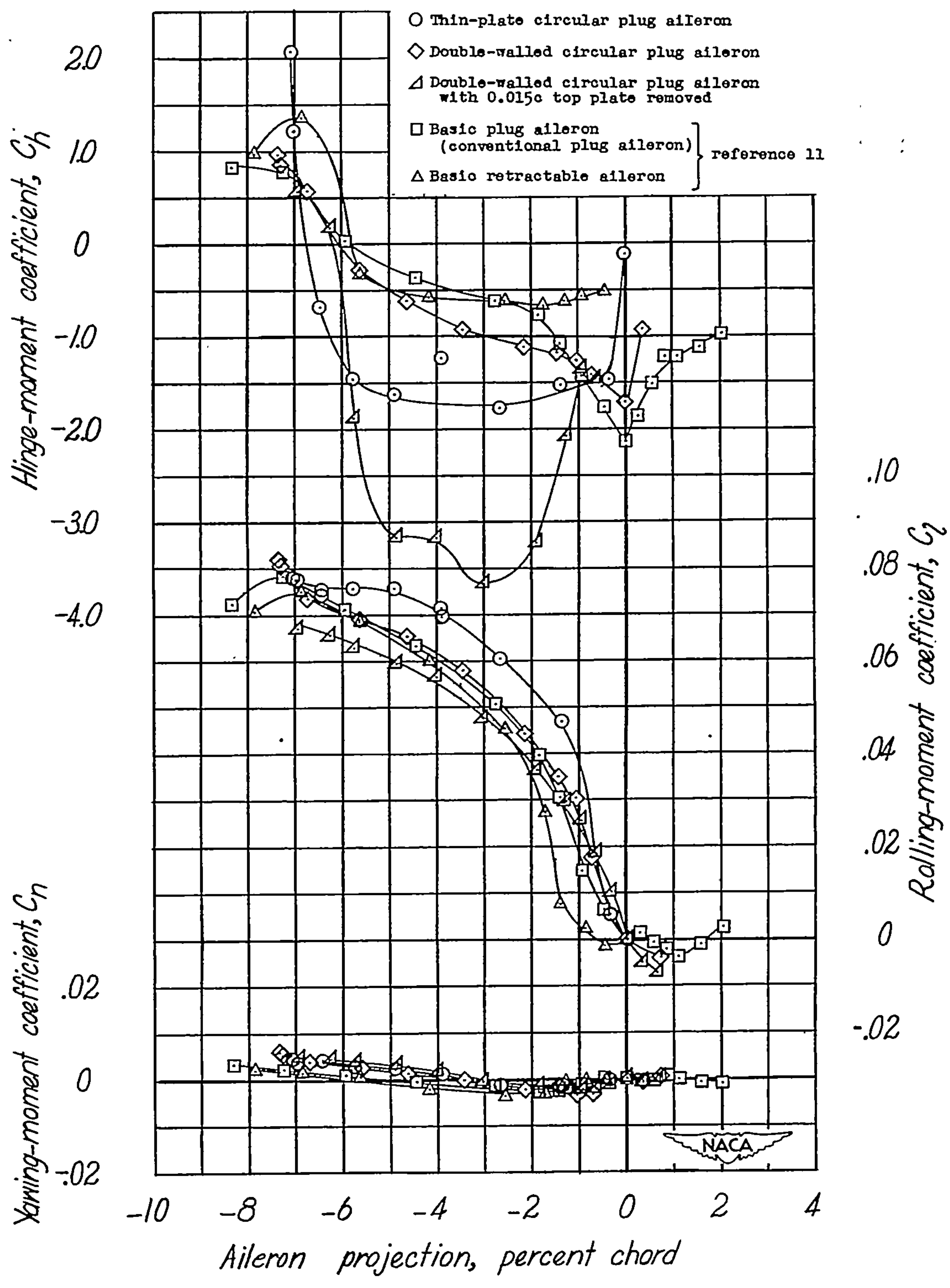

(a) $\alpha \approx 0.2^{\circ}$; $C_L \approx 0.12$; $M \approx 0.39$.

Figure 18.– Comparison of lateral-control characteristics of the three circular plug ailerons, a conventional plug aileron, and a retractable aileron investigated on the subject wing. Flap retracted.



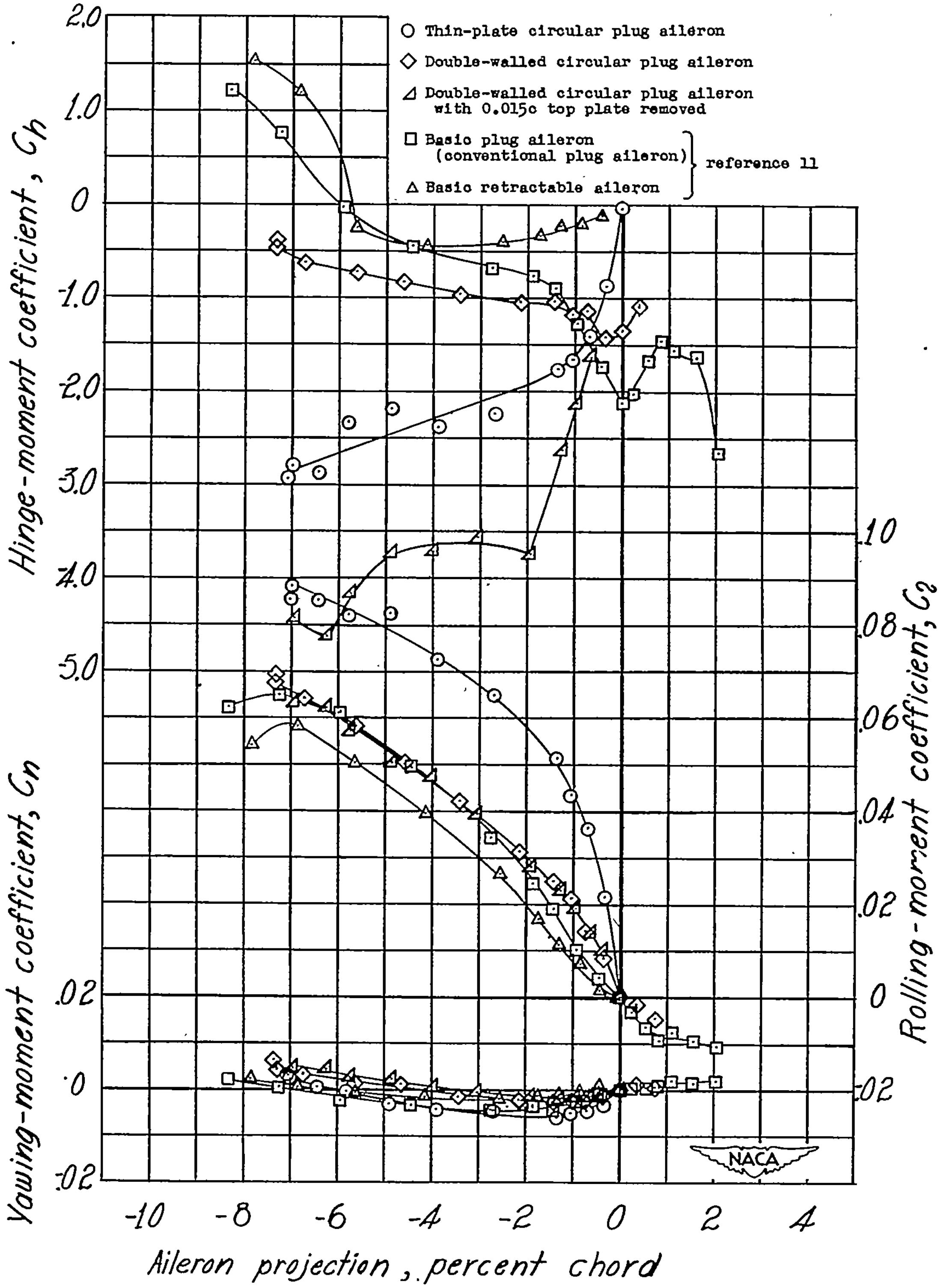

(b) $\alpha \approx 11.6^{\circ}$; $C_L \approx 0.94$; $M = 0.19$.

Figure 18.– Concluded.




(a) $\alpha \approx 2.6^\circ$; $C_L \approx 1.57$; $M = 0.27$.

Figure 19.– Comparison of lateral-control characteristics of the three circular plug ailerons, a conventional plug aileron, and a retractable aileron investigated on the subject wing. Flap deflected 45°.




(b) $\alpha \approx 6.9^\circ$; $C_L \approx 1.74$; $M = 0.13$.

Figure 19.– Concluded.

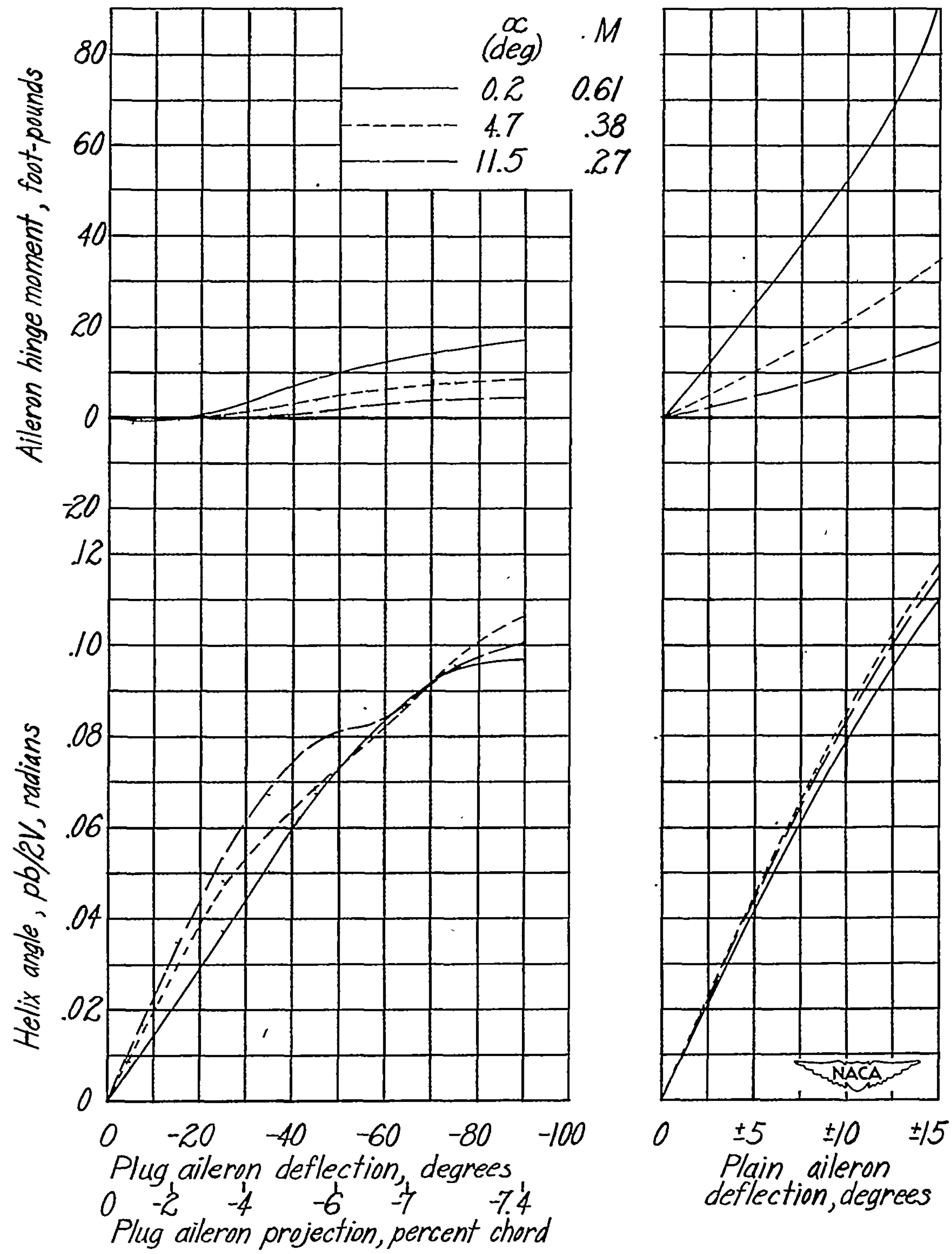



Figure 20.– Comparison of lateral-control characteristics of the double-walled circular plug aileron and a 0.20c, $0.38\frac{b}{2}$, sealed plain aileron investigated on the same wing (reference 10). Flap retracted.